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RECORDS

OF THE

GEOLOGICAL SURVEY OF INDIA

VOLUME 104, PART 2

REVIEW PAPERS ON
ENGINEERING GEOLOGY AND GROUNDWATER

Published by order of the Government of India

1972

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FOREWORD

The first ever descriptive and comprehensive account of the geology of India was compiled by H.B. Medlicott and his colleagues and published during 1879-87 as 'A Manual of the Geology of India'. The second edition, by R.D. Oldham, appeared fourteen years in 1893. The colossal amount of additional geological data that accumulated during the next 50 years necessitated a third edtition, in three volumes by E.H. Pascoe in 1950. Since then several other publications of the Geological Survey of India, under different series, have been brought out on minerals, stratigraphy, palaeontology, petrology, engineering geology, groundwater and geophysics.

For the first time Geological Survey of India now brings out, in one series of publications, the vast and up-to-date knowledge acquired by the department in its different spheres of activity. These volumes, reviewing the status of our geological knowledge in different fields highlighting the contribution of the department particularly in the post-Independence period, will be brought out in five successive volumes of the Records of the G.S.I., Part 2. They are :

Records, Vol. 100, pt. 2 : General and Research.
Records. Vol. 101, pt 2 : Stratigraphy.
Records, Vol. 102, pt. 2 : Mineral Deposits.
Records, Vol, 103, pt. 2 : Geophysics
Records, Vol. 104. pt. 2 : Engineering Geology and Groundwater.

It is sincerely hoped that this series will serve the purpose of spotlighting the up-to-date information on the subjects discussed.

In this volume, Records, Vol. 104, pt. 2, review papers on Engineering Geology and Groundwater, co-ordinated by Sarvashri B. Ramachandran and B. N. Niyogi, Geologists (Sr.), G.S.I. respectively are presented. The first seven papers relate to Engineering Geology and the last three to Groundwater.

Calcutta
20th April, 1972

M. S. Balasundaram
Director General

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ENGINEERING GEOLOGY

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RECORDS
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GEOLOGICAL SURVEY OF INDIA

VOL. 104 PART 2

HISTORY AND DEVELOPMENT OF ENGINEERING GEOLOGY IN THE GEOLOGICAL SURVEY OF INDIA

by

M. S. BALASUNDARAM, B. Sc (HONS), M.A.
AND
G. S. M. RAO, M. Sc.

Introduction

General

Of all natural resources, water is a basic necessity for support of life and also for growth of food and development of power. Water for drinking is obtained from rivers, tanks, wells and tubewells. Storage reservoirs are necessary for large scale irrigation and hydel power development. In the post-Independence period, dam building activities in the various river valleys in India rose to a phenomenal degree both for agricultural (green) revolution and power generation and incidental flood moderation. These activities stimulated study and application of engineering geology in the investigation of foundation of dams and bridges, stability of road and rail alignments and search for construction materials.

Engineering Geology is concerned with the applications of geological information combined with practice and experience to assist the engineer in the solution of problems, in which such knowledge is applicable. Lack of proper study and geological interpretation or failure to discover some relatively minor geologic detail may prove costly and sometimes hazardous. The construction of a dam to retain water causes more interference with natural conditions than does any other civil engineering operation. Therefore, very thorough appraisal of geological environment needs no special emphasis.

The engineering geologist has to use all available tools, up-to-date scientific and technological knowledge in this endeavour. He has to conduct an intensive survey of surface features as revealed by the study of photo-geology, tectonics, stratigraphy, structure, petrology, geoseismology and geohydrology. For assessment of sub-surface conditions he has to rely on the geophysicist and the driller. All the above aspects of geological studies have been known as 'geotechnic' since their application to the construction of Swedish railways in 1913. Karl Terzagi, the father of soil mechanics, has aptly stated that a knowledge of geology is as essential to a civil engineer as brewer's yeast to the baker.

Historical Review

The great epic of Mahabharata, Vedas, Smritis and other ancient classical literature contain numerous references about irrigation and water supply. Construction of embankments, bunds and canals on Cauvery river dates back to 200 A. D. Some of the more important activities towards utilization of water resources during the 19th Century are the construction of the Ganga canal in 1854, Godavari and Krishna canals in 1855, the 30 m.-high Khadakvasla dam near Poona in 1869 and the first hydel power-station near Simla in 1897. Diversion of the west flowing Periyar river in Kerala (Travancore State) into Tamil Nadu (Madras State) was accomplished by construction of the Periyar dam a little over hundred years ago. In all these structures, geological principles were taken into consideration by the construction engineers.

The first recorded advice on engineering geology by the Geological Survey of India was by T. Oldham during 1852, regarding the geological factors influencing the railway alignment between Calcutta and Patna. During 1884, the disastrous landslips of Birehi Ganga were investigated. During 1888-89, the Survey for the first time examined suitability of dam sites of the Marikarive, Chitaldrug district (Mysore State) and Bhavani dam, Coimbatore district (Tamil Nadu). In 1895 and 1896 measures to safeguard Government House Building at Nainital from landslides were suggested. During 1898-99 some of the dam sites in the then Madras State were investigated.

Oldham's original and classic work on the great Assam earthquake (1897) laid the foundation for the modern seismology in the World. Other major investigations carried out by the Geological Survey on earthquakes in the Indian sub-continent are : Kangra (1904), Dhubri (1930), Baluchistan (1931), Bihar-Nepal (1934), Assam (1950), Anjar (1956), Delhi (1961) and recently Koyna earthquake of 11th December, 1967.

Pre-Independence Period (1900-1947)

Since the beginning of the 20th Century, the Geological Survey of India was called upon to advise on engineering geology problems in a greater measure. As many as 105 investigations were attended to, of which some of the important ones were the Bhakra, Mettur, Thungabhadra, Jamuna, Lower Bhavani, Hasdeo and Pench projects. These are of very special significance, as most of these projects are now functioning. About six investigations were undertaken for railways of which particular mention may be made of the rail links between Assam and Bengal, Katni and Daltonganj, Mukerian and Mandi, Bombay and Sidh. Bridge sites across Banki *nadi*, Sun river, and Sadabaha *nadi* in Bihar, and the bridge site across Bramhaputra between Amingaon and Pandu were also investigated. Landslips at Muree, Darjeeling, Kalimpong, Nainital and Chamba were examined and remedial measures recommended.

Geological Survey of India rendered advice on some of the civil engineering projects in Burma and Baluchistan also during the above period. In Burma about 18 dam sites, six bridge sites and the railway alignment between Minbu and Pakokku were geologically assessed. Of these special mention may be made of the investigations for Hiangaw Lower Lake scheme, Rangoon, Thitson reservoir (Yamthein district), Tungai dam site (Southern Shan States), and Pathechung hydro-electric project (Toungoo district).

In Baluchistan and the North Western Frontier Province, about 18 dam sites were evaluated, of which the investigations for the hydro-electric scheme for Quetta, and Malakund and for the dam at Spinkarez near Quetta are worth mentioning. In addition, geological surveys for tunnels on Khyber railway, N. W. F. P., were also carried out.

Post-Independence Period (1947-50)

Till 1947, advice for the engineering projects was rendered on the basis of surface geological studies and the examination of the drill cores during short visits to the sites, since the schemes were all of small dimensions and located on sound terrains. But such a preliminary appraisal of the site conditions were found to be inadequate, when construction of large multipurpose projects like, the D. V. C., Hirakud and Bhakra were undertaken. Complex problems of site selection, evaluation of foundation conditions and treatment, assessment of the availability of construction materials and study of reservoir competency necessitated constant attention and advice from the geologist. For timely fulfilling these tasks adequately, Resident Geologists were posted for the first time at the project sites in 1947 commencing with Hirakud. The

number of engineering geological investigations till the commencement of plan period in 1951•was about 460.

Five-Year Plan Periods (I to III)

During the three Five Year Plan periods beginning from 1951 the items handled exceeded 1,700 in number. Majority of these (1,438) relate to the irrigation and power projects in this country. The number of geotechnical reports issued during First, Second and Third Five-Year Plan periods was 245 (1951-56), 463 (1956-61) and 654 (1961-66) respectively.

During the First Five-Year Plan period, commencing from 1951, this Division handled 266 investigations of which 131 were for Irrigation and Flood Control projects, 20 for hydro-electric projects, 25 for communication projects, 26 concerning hill-side slope stability problems, seven for building-site locations and 57 other miscellaneous investigations. This period marked the beginning of purposeful association of Engineering Geologist and Civil Engineers for the application of principles of applied geology to project planning, design and construction.

Development Of The Organisational Set Up

Strategic Branch

During the Second World War (1939-45), the strategic branch of the G. S. I. specially created for this purpose took up numerous and intensive investigations for construction of aerodromes, road alignments, sites for landing beaches and water supply mainly for defence requirements. Many technical bulletins on geology, water supply and construction materials were issued for the guidance of the defence personnel.

Engineering Geology and Groundwater Division

During the post-war period, activities in Engineering Geology increased enormously synonymous with the growth of irrigation and power in the country. This resulted in the creation of a seperate specialist Division, called the Engineering Geology and Groundwater Division in Geological Survey of India in 1945.

The specialist Division had only a compliment of six officers under the able and inspiring leadership of Dr. J. B. Auden, to carry out the enormous task of detailed geotechnical examination of irrigation and power projects in the whole country. The strength of this Division was increased to 18 in 1950, of which 12 officers worked as Resident Geologists at nine important dam sites to deal with the increasing work-load.

In 1957 (Second Five Year Plan) the Engineering Geology Division was bifurcated into sub-sections A and B for greater facility of work in the Northern and Southern parts of the country operating from Calcutta and Hyderabad respectively. These two sub-sections together handled 393 geotechnical investigations, of which 282 were for irrigation and flood control and 51 for hydel projects and the rest for communications, hill-slope stability and other miscellaneous works.

Regional set up of the five Engineering Geology Divisions

During the Third Five-Year Plan period, there was a further change in the Organisational set up of the Engineering Geology branch. In 1959, three Divisions came into existence operating from the Eastern, Northern and Southern Regional Headquarters of the Geological Survey of India, at Calcutta, Lucknow and Hyderabad respectively. This was further consolidated when the regional offices were established in 1961. Two more Divisions were established in Western Region at Jaipur and in Central Region at Nagpur in January and August, 1967 respectively. All these five Divisions consisting of 66 Engineering Geologists, are each under a Director or an experienced Senior Geologist.

Northern Region : The Engineering Geology Division of the Northern Region with headquarters at Lucknow attends to geotechnical investigations in the States of Uttar Pradesh, Punjab, Haryana, Himachal Pradesh, Jammu and Kashmir.

With the commencement of the first Five-Year Plan in 1951, the significant expansion of activities is seen from the geotechnical investigations numbering 54 in 1946-51, rising to about 254 in the Third Plan period (1961-66). During the Fourth Plan, the work-load is anticipated to be of the order of about 300 investigations in respect of high dams, large tunnels and massive Power Houses, most of them located in the complex Himalayan terrain.

This Division started with barely nine officers, and has now 30 officers. The Division has issued about 305 reports during the Third-Plan period.

Western Region : The Engineering Geology Division of the Western Region, constituted in January, 1967, at Jaipur, handles geotechnical problems of the States of Rajasthan and Gujarat, with a strength of seven officers. Resident Geologists have been posted at major projects like Ukai and Narmada in Gujarat, and Ranapratapsagar in Rajasthan. Feasibility studies for minor irrigation schemes have been taken up.

Eastern Region : The Engineering Geology Division of the Eastern Region with headquarters at Calcutta attends to the items in the States

of Orissa, Bihar, Bengal, Assam, Tripura, N. E. F. A., Manipur, Bhutan, Sikkim and Andaman Islands with 12 officers. During the Second Plan period it has rendered advice on important projects like Hirakud (Stage II). Damodar Valley Corporation dams such as Maithon and Panchet, Kangsabati etc. During the Third Five-Year Plan, the Division attended to geotechnical problems at Jaldhaka (Bengal) Barapani (Assam), Kothar and Gandak, Chandan, Morwe and Badua (Bihar) and Tikerpara and Naraj (Orissa).

During the first two Plan periods the Division carried out 586 investigations. In the Third Plan, 400 investigations were done and 600 investigations are proposed for the Fourth-Plan period.

Besides this, the Division attended to geotechnical examinations for border roads, factory sites, stability of hill slopes in Darjeeling area, West Bengal and the problems of siltation in the Damodar Valley reservoirs.

Southern Region : From 1959, the Engineering Geology Division attended to items in the States of Andhra Pradesh, Mysore, Goa, Madras, Kerala, Madhya Pradesh, Maharashtra and Gujarat. Investigations in Gujarat were transferred over to the newly formed Western Region in January, 1967 and those of Madhya Pradesh and Maharashtra to the Central Region in August, 1967.

This Division handled about 780 investigations concerning major river basins of the Narmada, the Tapti, the Godavari, the Krishna and the Cauvery. Investigations for photofilms factory site at Ooty, synthetic drugs factory at Hyderabad, tunnels for the D. B. K. Railway, Hassan-Mangalore railway alignment and the Vishakhaptnam Out-Harbour have also been attended to.

Central Region : The Engineering Geology Division of the Central Region at Nagpur started from August, 1967, attending to investigations for major projects like Tawa, Demba, Satiara, Narmadasagar and Barna in Madhya Pradesh and Koyna Stage III, Tulshi and Vaitarna projects in Maharashtra with 10 officers. It has advised on 14 other minor irrigation and hydel projects in Maharashtra and Madhya Pradesh.

In addition, this Division carried out the important Koyna earthquake (11th December, 1967) investigation.

Resident Geologists

Dams constructed in the country prior to 1947, had an average height of about 25 m. above the foundations, the present average being above 28 m. With the start of construction of high dams on less satisfactory foundations,

the need for a more quantitative assessment of the properties of soil and rock for foundations and suitability of construction materials assumed importance.

Construction of the 220 m. high concrete dam at Bhakra, 121 m. high Ramganga earth dam, 213 m. high Kishau dam and 137 m. high arch dam at Iddiki have necessitated evaluation of the foundation conditions and treatment based on most advanced techniques in soil and rock mechanics. Earlier methods of evaluation of physical properties of rocks on samples in laboratories have given places to more reliable methods of *in situ* tests of rock masses. This quantitative evaluation of the rocks of the foundation and abutments of dams under anticipated stresses has helped in the adoption of a rational and economic design.

Such detailed quantitative studies should be based on thorough assessment of the surface and sub-surface geology of these sites. Thus the need arose for posting Resident Geologists at many of the major construction projects like the D. V. C., Hirakud, Bhakra, Beas link, Rihand, Ranapratapsagar, Koyna Nagarjunasagar, Srisailam, Tawa, Sabrigiri, Parambikulam-Aliyar and Iddiki projects.

Status of Studies, Progress And Achievements

General Problems in the three Physiographic Units of India

The vast sub-continent of India with an area of 3,276 million sq.km. is physiographically divisable into three component units called the Peninsula, the Indo-Gangeta alluvial plain and the Extra-Peninsula comprising the Himalayas and associated mountain ranges.

The geomorphological and geological set up of the three physiographic units are vastly different. In the Peninsula the terrain comprises mostly of hard and competent rocks of antiquity (pre-Cambrian). The problems are mostly erratic rock decay, major faults, shears, fractures and master joints. On the other hand the problems are varied and complicated in the Extra Peninsula where the Himalayas are the dominant feature, comprising younger incompetent rocks which are faulted, thrusted, folded and shattered. Landslides, excessive erosion and rapid silting of reservoir and flood devastation create serious problems here in addition. Further they are situated in an active seismic belt subject to major earthquake in the past.

In the Indo-Ganga alluvium all structures have to rest on alluvial fill, requiring light weight design, taking cognisance of water table conditions.

The severe Koyna earthquake of 11th December, 1967, in the Deccan Plateau has raised a new problem in Peninsular India, so far presumed to

be aseismic. The geologists and seismologists are now of the view that certain narrow belts of the Peninsula, particularly the Western Coast of Maharashtra, are susceptible to major shocks, requiring adoption of seismic factors in the construction of structures here.

In brief the status of current work and proposals at hand in the Engineering Geology Divisions of the five Regions are dealt with below.

Northern Region : This region at present handles investigations for 11 major irrigation and power projects which are :-

1. Lower Jhelum Hydel Project, J & K.
2. Upper Sindh Hydel Project, J. & K.
3. Chineni Hydel Project, J. & K.
4. Beas Dam Project, H.P.
5. Beas Link Hydel Project, H.P.
6. Uhl Hydel Project, H.P.
7. Giri Valley Hydel Stage I, H.P.
8. Ramganga Dam Project, U.P.
9. Yamuna Hydel Project, U.P.
10. Obra Hydel Project, U.P.
11. Jamni Dam Project, U.P.

During the remaining Fourth Plan period construction stage investigations will be taken up for 10 projects including Salal, Sawalkot and Bursar dams in Jammu and Kashmir, dams on Uhl, Sutlej, Chenab and Giri rivers in Himachal Pradesh, the Thein dam in Punjab, Kishau dam, Tehri dam, Lakhwar dam, Pancheshwar dam, Rameshwar and Kotlibhel dams in U. P. In addition 30-40 smaller projects will be investigated in the next 10 years.

During the Fourth plan period, this Division will handle 600 investigations in the geologically complex terrains of north India, susceptible to earthquakes, landslides and rapid silting. A start has been made in this region in 1969 by taking up research work in geomechanics and construction materials.

Western Region : In Western Region, the Engineering Geology Division handles Ukai and Kadana projects in Gujarat State and Ranapratapsagar, Jawaharsagar and Damtikokra irrigation projects in Rajasthan. Investigations for minor projects such as Kanota, Jhadol, Unchakiya, Bilas, Hindlot, Wagli, Devas, Bandisendra, Sukri and Chandrana are under progress.

The major items of investigation include problems of providing cutoff in the earther section of Ukai dam, treatment of the buried channel in Kadana dam, stability and seepage studies of the abutments in Jawaharsagar dam.

In the Fourth Plan period construction stage investigations for Navgam dam across Narmada and other investigations in Gujarat and Rajasthan would be continued.

Eastern Region : Engineering Geology Division of the Eastern Region, has worked out geology of about 11 projects since constructed. These are Hirakud, Godahaddo, Budabudiani and Salandi in Orissa, D. V. C. dams in Bihar and Bengal, Jaldhaka and Mayurakshi dam in West Bengal and Morwe, Chandan, Badua, and Getalsud in Bihar. Resident Geologists at these project sites have in aggregate logged about 20 km. of drill cores, and about 1 km. of drifts.

Projects under constructions, that have been geologically investigated in detail are :—

1. Balimela Dam Project, Orissa.
2. Tenughat Dam Project, Bihar.
3. Barapani Stage II, Assam.
4. Gumti Hydel Project, Tripura.
5. Kangsabati Project, II Stage, West Bengal.
6. Farakka Barrage, West Bengal.

Eleven projects are under detailed investigation, for being taken up for construction. These include Joro-Harbangi project, Pitamahal irrigation project, Indravaty hydel project in Orissa, Tista barrage project in West Bengal, Lagyap hydel project in Sikkim, Chukha hydel project in Bhutan, Logtak in Manipur State, Umiam Stage III, Assam, Dhanikari dam project, Andamans and a score of minor irrigation and power projects.

Southern Region : The Engineering Geology Division of the Southern Region has been actively associated with the geotechnical work for Nagarjunasagar, Srisailam, Lower and Upper Sileru, Pochampad and Midpennar projects under construction in Andhra Pradesh. In Kerala, extensive studies have been carried out for Iddiki, Sabarigir, Lower Shloiyar and Kuttiyadi projects under construction.

In Tamil Nadu (Madras State), Parambikulam-Aliyar Kundah, Periyar, and Pykara, have been examined in great detail. Geotechnical investigations of Kalinadik, Malaprabha, Hidkal, Kaveri and Sharaswathy in Mysore State, have been carried out. Investigations for Sabeli and Dudhasagar projects at Goa have also been carried out.

Central Region : The Engineering Geology Division of the Central Region, is studying construction stage geology for Tawa Project in Madhya Pradesh and Koyna Stage III in Maharashtra. Works are under progress

for Demba, Narmadasagar, Satiara, and Barna projects and 10 other minor projects in Madhya Pradesh.

In Maharashtra geological interpretations have been *taken* up for Koyna, Tulsi, Manjra, Manyad, Kukadi, Kolkewạdi, Vaitarna, Upper Penganga, and Viroli projects. Advice has been rendered for railway tunnels between Poona and Miraj and for road tunnels through Malabar Hills in Bombay.

In the Upper Vaitarna and Koyna (Stage III) dam and tunnel, Maharashtra, special seismic factor has been introduced in view of the major Koyna earthquake of 11th December, 1967.

Present And Future Lines Of Studies

Since the middle of nineteenth Century (1852) geologists of the Geological Survey of India have been advising on problems of Engineering Geology. In the early stages certain broad recommendations were given based on surface observations. But during the post-Independence period subsurface exploration by geophysical methods and drilling came in a big way for foundation evaluation. Geologists carried out mapping on a large scale and interpreted weak features in foundations from surface and study of cores samples. Delineation of sub-strata and sound rock profile for foundation purposes were arrived at. Stability of cuts, landslides, problems of erosion, silting and reservoir competency were also studied. Besides location of suitable construction materials and areas prone to earthquakes were also geologically evaluated. But the geotechnical reports lack laboratory data on the test results of rock and soil samples. Test results carried out are often included, *perhaps without proper interpretation of the* problem. Provision of adequate laboratory facilities in the Geological survey itself would be the obvious solution.

With the completion of many dams between 1950 and 1970, most of the favourable sites for dam location would have been utilised. The dams in future would have to be located on incompetent and complex foundations. This would call for full evaluation of quantitative data on the strength properties of foundation and abutment rocks, for design studies. The future line of studies have to be aided by photogeology, for rapid evaluation of terrain conditions. Preparation of geotechnical maps for various river basins would be useful followed by laboratory studies of foundation and construction materials, with the aid of petrography, X-ray diffraction, spectroscopy, electronic soundings, differential thermal analysis of clays *etc.*

Weak foundations for civil engineering constructions and consolidation of the same by grouting processes need emphasis. These processes would ultimately depend on rock or soil characteristics like composition, texture, structure, state of preservation, crushing etc. Research on these aspects are best done by an experienced engineering geologist in collaboration with engineers working in projects under construction.

In 1947, tunnels for hydroelectric projects in the country were 16 km. long but this will now shoot up to about 225 km. by the end of the Fourth Plan. Therefore, rock deformation studies in the construction of tunnels and underground power houses will be necessary for quantitative data for design of the lining, supports *etc.*, Study of the stability of slopes of penstocks and susceptibility of power house sites and large open cuts to landslides have to be attended to also.

A scientific study of the causes of landslides with reference to (1) stability of slopes and (2) contribution of silt to the reservoir in the Himalayan region are essential for recommendation of sound preventive measures. Field studies of the landslide problems should also be backed by laboratory research on the mechanical properties of the slope material.

Systematic studies of construction materials, their availability and suitability are to be developed on the following lines :

(i) Assessment of suitability and standardisation of types required for various construction jobs.

(ii) Preparation of regional geologic maps showing the availability of construction materials.

(iii) Study on the types which promote alkali-aggregate reaction.

(iv) Studies on Pozzollonas.

(v) Evolving better techniques of quarrying to minimise waste.

(vi) Development of the use of light weight aggregates for construction in alluvial and sedimentary areas.

Laboratory Research

Establishment of a Rock Mechanics Research Laboratory with facilities for concrete and material testing is a necessity and should be created without further delay. In the main Research Laboratory, specialisation work like geomechanics, grouting research, geoseismology, geothermal investigations and compilation of geotechnical maps for each State can be carried out. Systematic petrographic studies on aggregates both coarse and

fine, study of clay materials and earth-dam materials could be carried out in the regional laboratories. Trained personnel are a must for systematic engineering geological studies. In India advance training facilities in engineering geology, seismotectonics, rock mechanics and geoseismology are inadequate. Therefore, a few officers may be trained initially abroad in these disciplines to build up necessary nucleus to train more officers locally. Importance of instrumentation in tunnels, dams and power-houses are fully realised. In all modern dams and other important civil constructions instruments are installed for measurements of water levels, uplift pressures, seepage, deformations and settlement *etc.* Perhaps the possible lines of research on these could be on 1) examination of the possibility of earth movements, (2) stability of slopes and prediction of rock slides based on rock mechanics, 3) Groundwater pressures by study of sub-surface water level fluctuations by creation of reservoirs *etc.*

Engineering Geology And National Economy

Irrigation and power development form the basis for agriculture and industry of any country. In India the irrigation potential is of the order of 75 million hectares out of a total cultivated area of 158 million hectares. At the beginning of the Five Year Plans in 1951 the area under irrigation was 22.66 million hectares. By the end of the Third Plan, of the 550 millard cu. m. of utilisable water, only 36% has been utilised. The hydro-power potential of the country is of the order of 41 m. kw. By the end of the Third Plan the achievement in power production is of the order of 10.17 m. kw. including thermal power. Hence an idea can be obtained about the immense task yet to be achieved in harnessing the river valleys for irrigation and power in India. In this endeavour the function of an engineering geologist is well known.

Development of Engineering Geology backed by laboratory research and its implication in more precise terms in the projects for irrigation and power should ensure 1) greater safety of structures and 2) economical design to cut down cost. Expeditious and successful completion of these projects will no doubt contribute to self sufficiency in food and more power for industrialisation leading to a substantial improvement in national economy and prosperity of the nation.

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The authors are thankful to the Director of Engineering Geology Divisions of the Northern and Eastern Regions, the Officers-in-Chargs of Western, Central and Southern Regions and Shri B. Ramachandran for providing data on the respective regions.

SYSTEMATIC GEOTECHNICAL STUDIES IN THE COUNTRY

by
V.S. KRISHNASWAMY, M. A.

Introduction

In the first decade of the Specialist Division in the Geological Survey, systematic studies in different stages of project-development involved application of various branches of geology, like geomorphology, economic geology, geohydrology, stratigraphy and structural geology, petrology and mineralogy, besides geophysics. In the subsequent 15 years, an increased application of the above branches of geology to problems of civil engineering started with a greater utilisation of geoseismology, geomechanics (earth sciences), soil mechanics, foundation engineering, sedimentation engineering and materials engineering (engineering sciences).

Pattern and Objectives of Systematic Studies

The systematic geotechnical studies of a Project have to be sequentially carried through phases of planning, design and construction and, post-construction. Each phase of studies is divided into two stages ; the quantum and period of the studies depend on the size and nature of the Project. The ideal pattern of such systematic geotechnical studies is given below :—

Systematic geotechnical studies

- Planning Phase
  - Reconnaissance stage
  - Site selection stage
- Design Phase
  - Project Report or Preliminary investigation stage
  - Specification or Pre-construction detailed investigation stage
- Construction Phase
  - Intial excavation stage
  - Final excavation stage
- Post-construction Phase
  - Evalution stage
  - Implementa tion stage

In the reconnaissance stage, the objective is to unravel basic geological set-up on 1 :1,00,000 maps and obvious geological features on which the technical and economic feasibility is based. In the site-selection stage,

preliminary geological mapping (1 : 50,000., 1 : 15,000 & 1 : 5000 scales) and minimum of sub-surface explorations (including geophysical surveys) of possible alternative sites, for selection of favourable site from geological and engineering considerations and location of the sources of construction materials are carried out.

In the Project Report stage the aim is detailed mapping (1: 1000) ; sub-surface investigations of the selected sites and for construction materials (by means of drill holes, drifts, pits and trenches) ; and field and labortory tests for preparation of preliminary designs and approximate cost estimates. In the specification stage, complete geotechnical information, for final design drawings, specifications for each unit of the Project lay-out and utilisation of the construction materials are obtained. The final estimation of the volume of excavations earth work, concreting, and tunneling, outlines of foundation treatment, quarrying methods and aggregate processing and tunnelling techniques are finalised alongwith.

During initial excavations periodically mapping of the excavations on a large scale (1 : 600 & 1 : 300) are done to assess revealed features. At this stage, design and construction modifications, if any, have to be made on account of new features encountered, or, greater extent of the features than visualised. In the final excavation stage, the geological features of the foundations, earth work or tunnel lining are recorded (1 : 100 to 1 :300) and the results of the remedial treatment are evaluated.

In the evaluation stage of Post-Construction studies assesment of geological features as recorded at the final grade and the behaviour of the structure as furnished by the embedded instruments and special surveys are under taken. Any anomalous behaviour not adequately covered by design provisions is rectified by corrective treatment. In some cases, this may require additional explorations or observations. In the implementation stage, results of the corrective treatment are geotechnically evaluated and recorded for future reference.

Systematic Studies

In the case of 15 major projects which have been investigated, completed or are under construction, the average percent cost of exploration by drilling, drifting, pitting and trenching, in terms of the total cost of the Project, is 0.26, the minimum being 0.08 and the maximum 0.83. If the cost of geophysical exploration, preliminary and detailed topographical mapping, construction of access paths to the various exploratory sites, laboratory and field tests, and soil exploration, are included, the total cost of investigations for a major project may range from 1% to 2% of its total

cost. This is generally considered to be the minimum desirable level of expenditure for effective planning, realistic design and safe construction of major projects.

The utility of carrying out systematic geotechnical studies would be apparent from the following review of the contributions to the different phases of studies of the river development in the country in the last quarter century (1945-1969). Limitations of space permit brief descriptions of selected examples ; details are available in the cited references.

Application of Geomorphology

Planning Phase : Geomorphological evaluation of the drainage patterns of the Ganga-Bhagirathi river system in the Middle Himalayas for the 200-250 m. high concrete dam of the Kotlibhel (Malakunthi) and Tehri Dam Projects in Pauri and Tehri Garhwal, U.P. (Krishnaswamy, 1965a), pointed to the 'existence of regional shear zones in approximately N.-S and E.-W. directions confirmed by subsequent exploration. As both the sites lay across such shear zones, 15-30 m. wide in the river section, rock-fill dams instead of concrete dams were considered feasible. For the Maneri-Bhali Hydel Project in Uttarkashi Distt., U.P., geomorphological evidence led to the interpretation of an epigenetic gorge of the Bhagirathi river, with an abandoned glacial gorge or 'fossil valley' on the right abutment (Pant, 1965). Special measures to control the anticipated leakage through the fluvio-glacial debris in the 'fossil valley' were recommended. Subsequent exploration by geophysical drilling and drifting, confirmed this finding. A similar 'fossil valley' of the Dhauliganga river at the Tapoban dam-site, with the interpretation of a fault zone in the epigeneitc gorge interpreted by mapping and a line of hot springs, led to the rejection of this site for the Tapoban-Pipalkoti Hydel Project, Chamoli District.

Design Phase : The glacial history of the Upper Alaknanda valley was considered for the 12.60 m. high diversion dams for the Nandprayag-Langasu Hydel Scheme and the Vishnuprayag Hydel Scheme in Chamoli District. Deep glacial scour was interpreted, as proved by later drilling, to range from 40-60 m. ; this feature modifying the lay-out and designs. At the Bursar dam-site on the Marusadar river in Doda distt., J. & K State, the interpretation of glacial moraine fill in the valley, resulted in abandoning of the site for a concrete dam. Later drilling proved this overburden to be more than 75 m. for a 150 m. high dam.

In contrast to the Himalayan environment, the geomorphological history of valleys is simpler under the Peninsular environment. The problems here relate to deep weathering of the bedrock and buried bedrock channels. At the Kalinadi gorge of the Supa-dam site in Mysore, although

the site chosen had a chord-height ratio of 3 : 1 for a concrete gravity or arch dam, the depth of weathering of the abutment rocks extended to the bed level of the river and even lower, resulting in the design of a rock-fill dam (S.R. Review, 1969). At the Moosakhand dam site in Varanasi distt., U.P., a buried bedrock channel in the Kaimur quartzites, occurring below 20 m. of alluvium in the foundations of the earth dam on the left flank, was delineated by special studies and the permeability of the fill material calculated (Hukku, 1965a).

Construction Phase : The classic example is that of the Madupatty dam in Kerala, where a regional pattern of shear zones were interpreted (Auden, 1951). The location of the dam was across one of these regional shear zones, extending for a length of 56 km. Change in the design of the dam was not possible in the advanced stage of construction. In the absence of systematic geological studies, deep weathering of the bedrock was detected only during construction in the Sholayar dam in the Western Ghats, Madras ; the Pykara dam in the Nilgiri hills, Madras and the Linganamakki dam, Mysore. The design changes were modifying a part of the dam from masonry to earth or rock-fill (Rama Rao, 1965 ; Murthy & Srinivasa, 1965). During the construction of the 34 m. high Meja earth dam in Mirzapur distt., U.P.., the fluvio-glacial origin of the 18 m. deep overburden in the river section, and the lower permeability of the boulde-clays therein, permitted omission of a positive cut-off. During the construction of the 55 m. high Kadana dam across the Mahi river in Panchmahal distt., Gujarat, the location of a buried channel led to the deepening of the cut-off trench of the earth dam in this reach (W.R. Summary, 1969).

Application of Geoseismology

Planning Phase : Geoseismological studies were carried out on a limited scale for the Bhakra Dam Project, Punjab ; the Kosi High Dam Project, Nepal ; the Teesta Dam Project, West Bengal ; and Damodar Valley Projects, Bihar and Bengal ; during 1945-50. The locale of the dam-site was analysed with reference to the past earthquakes in nearby areas, on which basis estimated ground-acceleration was furnished for design. In addition, on the Bhakra Dam Project, the status of activity of the Bhakra thrust was assessed, (Nickell, 1945 ; Hazra *et al*, 1959). In the case of the Kosi Dam Project, air-photo interpretation showed the Daling thrust to be seismically dead and the Naohan thrust to be active (Auden, 1951). For the aseismic design of the Damodar Valley Projects, the Gondwana faults were judged to be inactive since early Tertiary times (Auden, 1959).

Design Phase : On the Beas Dam Project, a review of the computed acceleration at the dam-site during the Kangra Earthquake of 1905, and

studies of the seismic activity of the Satlitta (Soan) thrust below the foundations helped in direction of a suitable seismic factor and other design provisions (Jalote, 1962 ; Krishnaswamy, 1962 a). Blast tests in deep drill holes with instrumentation furnished data on the natural free period of vibration of the foundations. For the aseismic design of the Beas-Sutlej Link Project, acceleration gradient curves were drawn for the Kangra earthuake of 1905 (Krishnaswamy, 1959a) and the activity of the various thrusts and faults in the project-area was evaluated (Hukku, 1962). The deep lake sediments of the hydel channel alignment was prone to increased accelerations (Krishnaswamy, 1959 a ; Hukku, 1962). Blast tests have been done and shaking table experiments with the prototype have been proposed for the Pandoh diversion dam. For the 135 m. high Ramganga Dam Project in U.P., the status of activity of the Kalagarh thrust, located below the dam foundation the Sarapdhuli-Dhikala thrust, lying 5 km. upstream of the dam ; and the Moradabad fault, in the basement, 20 km. south of the dam, were evaluated (Varma, 1962, 1963 ; Krishnaswamy, 1962b). Shaking table experiments were also carried out. Extensive evaluations have been undertaken for the 100 m. high Salal (Dhyangarh) dam project and other projects on the Chenab river in J. & K State. This included studies of the active Riasi fault (Main Boundary Fault) occuring 3 km. below the plotting of the epicentres of all recorded earthquakes of magnitude 5 and above and within a radial distance of 600 kms., their correlation with all the major known faults and thrusts in J & K State ; and the computation of the magnitude-frequency relationship of all past shocks at different radial distances from the Salal dam-site (Krishnaswamy, 1966a). For the Umiam Barapani project in Assam, located in the mezo-seismal area of the Great Assam Earthquake of 1897, the active status of the Chodrang and the Bordwar faults, occurring 112 km. and 48 km. from the dam-site were considered (Karunakaran, 1965). These showed displacement during the 1897 earthquake with the introduction of the highest possible seismic factor for the design of the dam.

Before the Koyana earthquake of 1967, little or no studies were carried out for the projects in the Peninsular region, as this was believed to be prone to only low-magnitude earthquakes. This earthquake and the 1969 Bhadrachal earthquake on the East Coast (magnitude 6.5, Richter) have stressed the need for detailed geoseismological studies in the future planning of the Paninsular Projects as well.

In addition to the detailed, local and semi-regional studies for Projects, regional studies have been carried out for the preparation of the Seismic Zoning Map of India in 1962, revised in 1966 (I.S.I. 1962, 1966). A second revision of this map, with emphasis on geotectonics, is under finalisation.

Application of Economic Geology

The application of this branch of geology is essentially in the planning phase. Systematic studies were carried out for submergence of minerals of economic value by the Hirakud Reservoir (Krishnaswamy, 1947). The investigation of limestones of near-by areas for cement manufacture (Krishnaswamy, 1946, Ghosh, 1950) and economic surveys for mineral based industrial development have also been undertaken here. On the D.V.C. Projects, studies indicated that only Aiyar (now Tenughat) and Bokaro reservoirs, would submerge useful coal deposits. The height of Panchet reservoir was reduce to prevent the excessive submergence of the adjacent coal fields (Hazra and Krishnaswamy, 1957). The mineral resources of the Damodar Valley and the adjacent areas were examined for their utilisation for industrial development (Khedkar, 1950). At Rihand project, the height of the dam was limited to avoid the submergence of portions of the Singrauli coal-field. The economic potentialities of the marble deposits at Belwadih and the corundum deposits near Pipri, were examined before submergence (Rao 1965). In the case of the Dhyangarh high dam Project, J & K, the investigations revealed submergence of good quality bauxite (Auden, 1950), which was ruled out by later modifications. The Banasogar (Demba) project in Rewa distt., M. P., studies have indicated that some of the high grade limestone here will be submerged (C. R. Summary, 1969).

Application of Geohydrology

Planning Phase : The indirect effects of the Hirakud reservoir on the adjacent Rampur coal-field and the Panchet reservoir, D. V. C. on the adjacent Jharia coal-field, have been evaluated by geohydrological studies (Krishnaswamy 1959b ; Makkenjee and Roy, 1965). Because of effluent configuration, high levels of saturation, and low permeability of the sandstones, the impact of the reservoir on the coal-fields will be negligible. The reservoir readings, taken in 1959, confirmed this conclusion.

Design Phase : In the case of the Beas reservoir, H. P. investigations indicated that the reservoir on pervious Upper Tertiary and Quaternary formations will be subject to a temporary losses only, with no permanent loss, because of the synclinal nature of the basin (Soan syncline) and other structural barriers to flow (Krishnaswamy *et al*, 1963). The ânticipated changes in the piezometric head in the Upper Siwalik artesian aquifers of low permeability, occuring below the dam and the power house, led to drainage by means of tunnel in the abutments and by relief wells at the power house (Jalote *et al*, 1965).

The most useful applications of geohydrology have been in relation to the reservoirs proposed on limestones and dolomites. The classic case is that of the Kopili dam site in Assam, on plateau type of the Karstic Eocene limestones (Balasundaram and Gangopadhyaya, 1965a). Detailed studies included the loss of river discharge and injection of common tracers like brine and radio-active tracers like tritium into the cavernous limestones, to establish the direction and pattern of ground-water movement. The feasibility of this project in terms of reservoir leakage could not be quantitatively assessed (E. R. Summary, 1969). In the 30 m. high Obra reservoir, now being impounded on cavernous Kajrahat limestones (Lower Vindhyan) prospects of leakage exist by-passing the dam or emerging out at the distant outlets in the adjacent Son valley. Intensive and costly grouting of the entire thickness of the Kajrahat limestones along the eastern rim of the reservoir have been necessitated (Hukku and Mathur, 1965b). The proposed 100 m. high Dhyangarh reservoir in Udhampur distt., J. & K. State, on dipping Permo-Carboniferous Sirban dolomites have been proved to be water-tight by the absence of major caves and the presence of structural barriers to flow, (Chaturvedi & Tiku, 1965). Estimates of the temporary water loss and regain due to periodical recharge and discharge of a portion of the rim rocks have been made for this project (Ashraf & Waza, 1969). Studies of the 122 m. high Lunot reservoir for the Siul hydel scheme in H. P., proposed on low-dipping Permo-Carboniferous limestones, indicated loss of 15 cusecs at a head of 12 m. in the river section and an interpreted loss of 120 cusecs at full reservoir head (Ghosh, 1967). Hence an alternative lay-out was prepared. The investigations for the Paisuni reservoir, proposed on low-dipping Tirohan limestones (Lower Vindhyan) in Banda distt., U. P., led to the shifting of the alignment to avoid the limestone horizon (Hukku & Chaturvedi, 1966). Further studies are in progress now to determine impervious cover over the limestones in the reservoir area.

Construction Phase : On the Moosakhand dam project, U. P., interpreted leakage through buried channels, was confirmed during the construction and post-construction stages. Hence relief wells piercing the buried channel were provided (Hukku, 1967).

Application of Geophysics

The application of geophysics in the different stage of project development can be grouped under the following four categories :

A—Structural investigations of tunnel routes, dam-sites and reservoir sites.

B—Geohydrological investigations at dam-sites and reservoir sites.

C—Foundation engineering investigations at dam-sites, power house and related sites.

D—Construction materials investigations.

The results of application and the extent of success achieved have been discussed more fully in GSI. Rec. 103, Pt. 2.

Application of Stratigraphy and Structural Geology

Planning Phase : The exact relationship of the granites associated with the Chail thrust sheet was of importance to the lay-out of the 13 km. long 9 m. diameter Pandoh-Baggi tunnel of the Beas-Sutlej link project, H. P. Regional stratigrahical and structural evaluation indicated the granites, forming part of the higher Jutogh *nappe*. Studies in the project-area indicated intrusive origin for the granites (Krishnaswamy., 1961). Hence there is no structural weakness in the tunnel crossing of the contact between the Chails and granites. Subsequent drilling and trenching, confirmed it (Srivastava, 1965). Tunnelling through this contact was devoid of any trouble. For the Yamuna hydel project, U. P., and the Giri hydel project, H. P., the disposition of the Krol and Nahan thrusts were significant, because of the anticipated difficulties in crossing the intra-thrust zone by a 3 to 7 m. diameter tunnel, and the prospects of seismic movement along these thrusts (Auden, 1942). These major structural features, aligned across the tunnel could not be avoided, except by long water conductor or constructing costlier dams (Mehta and Dua, 1965).

Design Phase : On the Yamuna and Giri hydel projects, mapping of the tunnel alignment and its vicinity on 1 : 15,840 scale, and selected sections of the intra-thrust zone on 1 : 1000 scale as well as exploration by drifts and drill holes of the two thrusts at shallow depths were carried out. On the basis of studies the tunnel was re-aligned so as to cut down the width of crossing of the intra-thrust zone by 1/3rd to 1/2 the original width (Krishnaswamy, 1968b ; Shome & Dayal, 1968). On the Giri project, HP., the penstock alignment crossed the active Markanda thrust. By large scale mapping and exploration by drilling the power house location was modified to avoid the crossing of this thrust by the penstock (Shome and Dayal, 1966). For the Sundernagar-Sutlej tunnel of the Beas-Sutlej link project, nine alternative alignments were considered for avoiding, or, for minimal crossing of 4 major tear fault zones, whose width of crushing ranged from 150 to 300 m. as indicated by largescale and 3 km. of drilling. The final alignment had four kinks, to avoid weak zones and difficult tunnelling conditions (Krishnaswamy, 1965c). In the tunnel alignment for the Jaldhaka project in West Bengal, water-saturated terrace deposits

along the tunnel route necessitated provision of three kinks in the tunnel alignment, to avoid these deposits, ensuring adequate lateral and vertical cover. The design of the surge shaft was also modified because of the presence of the terrace deposits (Sen Sarma and Chowdhury, 1965).

The location of faults and shear zones in the design phase of studies has led to significant modification of the location and lay-out of dams. Examples are numerous ; a few typical ones are discussed. The classic case is that of the Marora dam-site in Garhwal, U. P., where exploration by drifts led to the discovery of a major fault zone in the abutment and shelving of the proposal for a 200 m. high concrete dam. In Assam, the dam site No. 1 had to be abandoned in preference to site No. 2, because of a fault zone in the river-bed (Karunakaran, 1965). In the case of the Tehri dam project, U. P., the presence of a 15 m. wide shear zone, led to the choice of a rock-fill dam. Likewise, the site for a 250 m. high arch dam on the Sutlej river at Aina, H. P., indicated a fairly wide fault zone on the left abutment. This feature, as well as the narrowness of this abutment led to the abandoning of the site.

Three alternative sites for the 140 m. high Navgam dam on the Narmada river, Gujarat, were explored, the final site chosen on the basis of minimum number of faults crossing the alignment (Raju and Shenoy, 1965). In the case of the Tenughat Project, Bihar, the spillway for the 56 m. high earth dam, was shifted to the right bank because of the deep weathering of the bedrock adjoining the fault on the left bank (19-47 m.).

Construction Phase : During the excavation of the power house cavity in the thinly bedded limestone and slates at Chibbro, Yamuna Hydel project, U P., by studies of the joint patterns and other discontinuities and the stereographic plotting of these features a suitable pattern of remedial treatment to support the walls of the power house cavity was evolved (Jalote, 1968). In grouting the foundations of Barapani dam, Assam, the evaluation of joint patterns played a notable role (Balasundaram and Gangopadhyaya, 1965b).

There are many examples of dams where faults and shear zones have been located during construction phase. Selected examples are listed. In the case of the Liganmakki dam and Hidkal dam, Mysore, existence of fault and shear zones on the foundations changed the design of the dam (Murthy, Srinivasa, 1965 ; Ali and Rao, 1965). In the case of the Nagarjunasagar dam, A. P. (Rao, 1965), Hirakud Dam, Orissa (Ramchandran & Acharya, 1954), the D. V. C. dams, Bengal and Bihar (Sundaram and Ramchandran, 1966) and a number of other dams, suitable remedial treatment had been accorded to these weak zones, on the basis of exploration and field tests.

Application of Foundation Engineering

Planning Phase : In the case of the Obra earth dam, U. P., the cavernous limestones bed at open valley site chosen earlier, called for enormous foundation treatment to control leakage. Alternative upstream sites necessitate either deep excavations for a chute spillway, and long tunnels for conveying the cooling water to and from the Obra Thermal Power Plant downstream. The cost studies favoured the open valley site, with the dam shifted downstream to the shales underlying the limestone sequence and extensive remedial treatment of the limestones below the eastern rim (Hukku aad Mathur, 1965b). The selection of a rock-fill structure for the 230 m. high Kishau dam, instead of an arch or gravity dam, was dictated by the narrowness of the left abutment, extensive gravitational gliding and a number of low-dipping shear zones in this abutment, and by the 60 m. thick carbonaceous shale-bed dipping at low angles downstream all of which involved difficult and costly treatment (Krishnaswamy *et al*, 1965b).

Design Phase : The lay out of the composite dam at Hirakud and at Konar D. V. C., was guided by the results of exploration. In the case of the Tilaiya dam, D.V.C., the geologic set-up favoured a concrete structure. The spillway of the weir for the Bokaro Thermal Station, D. V. C., in the river section, was shifted to the right bank, to avoid extensive treatment of a fault zone in the river bed (Hazra and Krishnaswamy, 1957). Detailed exploration led to a revised lay-out of the deep-set power house at Kota dam, Rajasthan, to minimise the prospects of sliding on shale layers in the Bhander sandstones (Varma *et al*, 1965). A 91m. wide shear zone in the Deccan basalts at the site of the 67 m. high earth dam at Ukai in Surat distt., Gujarat, was proved by intensive drilling. Large scale field permeability tests in the shear zone helped to work out measures to control leakage and piping. In the case of the Chandan dam, Bihar, the evaluation of rock conditions at the foundation grade, led to construction of a simpler gravity type instead of a costlier chute spillway. The lay-out of the curved Tenughat spillway was also guided by the prevailing rock conditions (E. R. Summary, 1969). The spillway location for Moosakhand dam was shifted from the river section to the right flank to obtain adequate width of the rock to resist sliding along horizontally disposed this shale layers amidst Kaimur sandstones with a concrete shear key at the axis.

The exploration of the right abutment of the 18 m. high Pandoh dam, H. P., by eight drifts, totalling 1 km. in length, indicated gravitational gliding in the right abutment to a depth of 30 m. into fresh rock. Mapping of the affected area indicated the quantity of unsound material to be 1m. cu. m., hence the proposed concrete buttress dam was changed to a rock-fill

with the axis of this dam reoriented to avoid the slide zone (Srivastava, *et al*, 1965).

Construction-Phase : During the construction of Ranapratap Sagar dam thin clay gouge seams (representing crushed and altered shale beds) were encountered in the horizontally bedded Kaimur quartzites. There were no traverse joints to permit sliding on these seams. Hence the toe of the dam was loaded with earth and rock-fill, besides providing shear resistance through steel dowel rods at the heel of the dam (Chaturvedi and Ashraf, 1965). In the power dam section many clay gouge seams were exposed in the 30 m. deep power house excavation at the toe of the dam. Shear resistance was provided through pre-stressed cables in drill holes at the toe of the dam (Varma, *et al*, 1965).

Application of Rock Mechanics

Planning Phase : The completed underground power houses in the Pre-Cambrians at Maithon D. V. C. and in the Deccan traps at Koyna involved only problems of jointing because of over-all competency of the rocks. Similarly, the locations for underground power house in granites at the Idikki project, Kerala and in charnockites and granites-gneisses at the Kadamparai hydel project in Coimbatore, Madras, have been favoured by the soundness of rock (S. R. Summary, 1969). However, at Mahi project, Rajasthan, an unusual underground power house location below the rim of the Bajaj-Sagar was selected, aligned parallel to the trend of the amphibolite on the basis of exploration by a deep shaft and a cross cut at the base. In contrast, the selection of an underground power house in the Himalayan environment at Chibbro, for the Yamuna Hydel Scheme, U. P., needed exploration of six sites by large-scale mapping and by 1 km. of drilling and 600 m. of drifting (Mehta and Sanganeria, 1965).

Design Phase : Bhakra was the first project on which detailed laboratory and field tests were conducted to establish the rock mechanics properties of the foundations (Bhatnagar and Shah, 1964) which led to a proper appreciation of foundation behaviour and the pattern of remedial treatment. Later similar tests have been carried out for the Nagarjunasagar and Srisailam projects, A. P., and the Idikki Project, Kerala. Small scale and large scale *in-situ* shear tests have been carried out for the Ranapratap Sagar and Kota Dam projects, Rajasthan and Srisailam Project, A. P., for assessment of sliding of shale seams in the foundations. Design provisions to counter sliding at the Srisailam dam included wedge shaped excavation ; curved layout for spillway dam and monolithic concrete without contraction joints to permit arch action (Design Note, Dams-III, C. W. P. C., 1969). On the Yamuna hydel project, U. P., flat jack tests

to evaluate the stress fields at the underground power house were carried out for the first time with indigenous resources (Tandon, 1966). On the Tehri dam project, U. P., extensive *in-situ* tests in exploratory drifts determined the modulus of deformation of the abutment rocks, the stress-deformation curve correlated with the geological site conditions (Narula, 1968) On the Beas dam project, H. P., and the Ramganga river project, U. P., the prospects of planar sliding in the tunnel intake area were studied in detail (Bhatnagar and Shah, 1967, Srivastava, 1968 ; Krishnaswamy, in Design Memo : Ramganga, 1967).

Construction-Phase : The utility of rock mechanics has been amply demonstrated during the construction of the first underground power house in the Himalayas, where positive support through pre-stressed cables has been given to the walls of the power house cavity (Tandon, 1968, Jalote, 1968). In the Yamuna tunnels, a pattern of smooth blasting, as well as prior perforbolting to control overbreaks have been adopted (Shome, 1968). Shotcreting, as a form of temporary support, has also been successfully tried on this project (Singh, *et al*, 1968). Control of overbreak, has been successfully attained during construction of the tunnels of the Idikki project, Kerala (SR Summary, 1969) and the tunnels of the Chineni hydel project, J & K (Srivastava, 1968). Evaluation of rock load for tunnel lining, following the earlier concept of Terzaghi, has been adopted for the construction of the Nagarjunsagar tunnels and a number of other tunnels in the Himalayas (Seshadri, 1968 ; Ashraf *et al*, 1968 ; Agarwal and Sondhi, 1968). On the Jaldhaka Project, W. B., the lining thickness was reduced on the basis of *in-situ* tests of modulus of elasticity (Sen Sarma and Chowdhury, 1965). However, the latest trend in design does not take into account the rock-loads for permanent lining in hard rock reaches (Krishnaswamy, 1968b). In fact, for the Sakarpathi tunnel of the Parambikulam-Alitar project, except for weak rock zones, the pressure tunnel in Pre-Cambrians is proposed to be left unlined (S. R. Summary, 1969).

Application of sedimentation engineering

Planning Phase : The primary role of the geomorphology and geological history of catchment areas for evaluations of silt loads of Indian rivers has already been emphasised (Auden, 1950b). The limitations of application of the Khosla formula for calculation of the sediment loads in the orogenically young Himalayan catchment areas with erodibble formations have been stressed (Auden, 1951).

Design Phase : The proposal of a silt detention dam at Wodhapura on the Pohru river, a tributary of the Jhelum in J & K State, led to studies

on the silt yielding potential of the various formations in the catchment. The most active silt yielding areas interpreted to be in the Karewas occurring below the dam site. Hence, the utility of the proposed dam for silt detention has to be reconsidered seriously (Krishnaswamy and Tiku, 1965d).

Construction Phase : The siltation of some of the completed reservoirs and those under construction in the Himalayas (Beas, Bhakra, Ramaganga) has been assessed on the basis of geological factors for forecast of total siltation, This has been proved to be more realistic than the present methods based on the Khosla formula (Krishnaswamy and Jalote, 1966c).

Conclusions

The foregoing review would indicate the value of systematic geotechnical studies in the planning of River valley projects, as these have led presentation of an exact picture of the situations obtained during construction, and design and cost provisions to be made for the same. On a large number of projects, the studies have been found exceedingly valuable because of the saving in cost on account of the choice of a better site, a better dam or a nearer source of construction material. The studies have also resulted in significant contributions to the adoption of special design measures and formulation and guidance of effective foundation treatment for ensuring the safty of the structure.

It was stated earlier that the systematic surveys and geotechnical studies would call for an expenditure of around 1% to 2% of the total cost of the project. The foregoing review of the utility of the studies would show that a premium of 1% to 2% of the project cost is well worth paying for ensuring the benefits of realistic planning and costing, safe and adequate design and speedier and economical construction of engineering projects in the country.

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References

AGARWAL, A. N. and SONDHI, S. N., 1968.—Geological basis for the evaluation of rock Loads on the Uhl Hydel Project, Himachal Pradesh. *Abstract. Symp. Rock Mechanics, Ind. Soc. Eng. Geol.*, p. 13.

ALI, H. and RAO, P. V. C., 1965—The geology of the Hidkal dam site Mysore and its influence on the design of the proposed dam, *Symp. River Valley Projects, Ind. Soc. Eng. Geol.*, P 9.

ASHRAF, Z. and NAG, R. B., 1968.—Geological basis for the evaluation of rock loads on the Chienni Hydel Project, Jammu and Kashmir, *Abst. Symp. Rock Mech. Ind. Soc. Eng. Geol.*, p. 9.

ASHRAF, Z. and WAZA, J. L., 1969.—Progress Report on the detailed geological investigations for the Salal Hydel Project, *Rep. Geol. Surv. Ind.* (unpublished).

AUDEN, J. B., 1942.—A geological investigation of tunnel alignments for the Yamuna hydel project, *Rec. Geol. Surv. Ind*, Vol. 77.

AUDEN, J. B., 1950b.—Some factors concerning transport of sediments by rivers, *Proc. Nat. Ins. Sci.*, Vol. 16., No. 6.

AUDEN J. B., 1950a.—The Role of geology in Multipurpose Projects *Proc. Nat. Ins. Sci.*, Vol. 16, No. 6.

AUDEN J. B., 1951—Role of geology in Multipurpose Projects, Presidential Address ; *Indian. Sci. Cong.*

AUDEN J. B., 1959—Seismicity of the Damodar Valley Projects. *Proc. First. Symp. Eqk. Eng., Roorkee.*

BALASUNDARAM, M. S. and GANGOPADHYAY, S, 1965a.—Cavernous limestone and the problem of reservoir leakage of kopili Hydel Project, Assam, *Abst. Symp. River Valley Projects., Ind. Soc. Eng. Geol.*, p. 14.

————————, 1965b.—Foundation geology and grouting of Umiam (Barapani) dam, Assam, Summary *Symp. River Valley Project, Ind. Soc. Eng. Geol.*, P. 20.

BHATNAGAR, P. S. and SHAH, S. R., 1964—Experiments on Bhakra dam foundations. *Proc. Int. Cong., Large Dams.* Vol. 1., p. 1081-88.

BHATNAGAR, P. S. and SHAH, S. R., 1967—Stability of Excavated slopes groundi ntake area, Beas dam at Pong, *Proc. Int. Cong., Large Dams*, Q. 32, R. 67. pp. 1051-1067.

CHATURVEDI, S. N. and TIKU, A. K., 1965—Geological studies to determine the prospects of leakage through the Sirban limestones, Salal reservoir area, Jammu & Kashmir, *Abst. Symp. River Valley Projects, Ind. Soc. Eng. Geol.*, p. 16.

CHATURVEDI, S. N. and ASHRAF, Z., 1965—Geological difficulties during the construction of the Ranapratapsagar Main and saddle dams, Rajasthan. *Abst. Symp. River Valley Projects, Ind. Soc. Eng. Geol.*, p. 11.

DESIGN NOTE, C. W. & P. C. DAMS II & III, 1969—Notes on design provisions for geological features of earth and concrete dams in India, personal comunication from Director, Dams II & III, Central Water & Power Commission, New Delhi.

GHOSH, D. K., 1967—Application of geohydrology to the investigation of the Siul Hydel Project, H. P., Paper presented before N. R. Centre, *Ind. Soc. Eng. Geol.* (Aug.)

HAZARA, P.C.D., and KRISHNASWAMY, V. S., 1957—Geology and Engineering Projects, *Indian Mining Journal*, Vol. V, No, p. 10 35-46.

HAZARA, P.C.D., and KRISHASWAMYY VS and Swaminath, J., 1959—Regional geology and seismicity of the Bhakra Dam Project. *Proc., Ist. Symp. Eqk. Engg., Roorkee.*

HUKKU, B. M., 1962—Geological evaluation of the thrusts and faults in the vicinity of the Beas Sutlej Link Project and the Uhi Hydel Project, Himachal Pradesh. *Proc. 2nd Eqk. Symp., Roorkee.*

————————, 1965a—On the control of leakage and piping through burried bedrock channels at the Moosakhand dam-site, Uttar Pradesh Abst *Symp. River Valley Projects, Ind. Soc. Eng. Geol.* p. 14.

HUKKU, B.M. and MATHUR, S. K., 1965b—Geological problems relating to the plan-design and first phase of construction of the Obra Hydel Project on cavernous limestones of the Lower Vindhyan, Uttar Pradesh.

HUKKU, B.M., and CHATURVEDI, S. N., 1966—Problems of planning and remedial foundation treatment of hydro-electric and irrigation projects, in Southern U.P. Abstracts, Symp. River Valley Project and National Planning. *Nat. Inst. Sci. Ind.*

HUKKU, B. M., 1967—A note on the landward rise of the hydraulic gradient in the buried channel fill at the Moosakhand dam-site, Varanasi District, U.P., *Rep. Geol. Surv. Ind.* (Unpublished).

INDIAN STANDARDS INSTITUTION, 1962 and 1966—Standard on Earthquake Resistant Design of Structures.

JALOTE, S. P., 1962—Studies relating to the seismicity of the Satlitta thrust, Beas Dam Project. *Proc. 2nd Symp. Eqk. Engg., Roorkee.*

JALOTE, SP., JAISWAR, HP., and GHOSH, D. K., 1965—Role of geology in the planning design and construction of the Beas Dam Project, *Abst. Symp. River Valley Projects, Ind. Soc. Eng. Geol.*

JALOTE, S. P., 1968—Geomechanical considerations in relation to the stability of the underground power house at Chhibro Yamuna Hydel Project, Uttar Pradesh *Abst. Symp. Rock. Mechanics, Ind. Soc. Eng. Geol.*

KARUNAKARAN, C., 1965—Geological features of the Umiam Barapani Project area. *Abst. Symp. River Valley Projects, Ind. Soc. Eng. Geol.*, p. 2.

KRISHNASWAMY, V. S., 1954—A preliminary report on the petrographic studies of Pozzolan-samples and concrete aggregate from the Hirakud Dam Project, Orissa., *Rep. Geol. Surv. Ind.* (Unpublished).

————————, 1959a—Seismicity of the Beas-Sutlej Link Project, *Proc. Ist. Symp. Eqk. Engg., Roorkee.*

————————, 1959b—Effect on the Hirakud Reservoir on the Rampur Coalfield. *Rep. Geol. Surv. Ind.* (Unpublished)

————————, 1961—Geological notes on the Beas-Sutlej Link Project, *Symp. Role of Geography and Geology in Engg. Projects, Abst., Ind. Sci. Cong.*

————————, 1962a—Probable correlation of the structural and tectonic features of the P and HP reentrant with the patterns of seismicity of the Region, *Proc. 3rd Symp. Eqk. Engg.,* Roorkee.

————————, 1962b—Significance of the Moradabad fault etc. in relation to the Ramganga River Project. *Rec. 3rd Symp. Eqk. Engg., Roorkee.*

KRISHNASWAMY, V. S, HUKKU, B. M, and CHATURVEDI, S. N., 1963—Geohydrological studies of the Beas Reservoir, *Proc. Symp. Ground Water, Misc. Pub. 14, Geol. Surv. Ind.*

KRISHNASWAMY, V. S., 1965a—Structural control for the anomalous meanders along the Ganga and Bhagirathi rivers. *Abst. Symp. Geomorphology,* Saugor University.

KRISHNASWAMY, V.S, MEHTA, P. N. & SHOME, SK., 1965b—Geological considerations pertaining to the choice of the site and type of the dam for the Kishau dam Project, Yamuna Hydel Scheme, Uttar Pradesh *Abst. Symp. River Valley Projects, Ind. Soc. Engg. Geol.,* p. 2.

KRISHNASWAMY, V.S. 1965c—Geological problems of the Sundernagar Sutlej tunnel alignment, Beas Sutlaj Link Project, Himachal Prodesh, *Abst. Symp. River Valley Projects, Ind. Soc. Engg. Geol.*

KRISHNASWAMY, V.S., & TIKU, A. K., 1965d—Annual Report, *Rec. Geol. Surv. Ind.,* V. 99, Pt. 1, p. 182.

KRISHNASWAMY, V. S., 1966a—Geoseismological considerations relating to the planning and design of the Salal Hydel Project, and other Lower Chenab Valley Hydel Projects in Jammu and Kashmir, *Proc. 3rd Symp. Eqk. Engg., Roorkee.*

KRISHNASWAMY, V. S., and R. S. VARMA, 1966b—Geological considerations relating to the treatment of prospective landslides in the left abutment of Ranapratap Sagar Dam etc., *Rep. Geol. Surv. Ind.* (Unpublished)

KRISHNASWAMY, V. S. and JALOTE S. P., 1966c—Engineering Geology of the Jhelum, Chenab, Ravi, Beas, and Sutlej river basidns in Kashmir and Punjab Himalayay, *Abst. Symp. River Valley Projects in National Planning, Nat. Inst. Sci. Ind.*

KRISHNASWAMY, V. S., 1968a—Rock loads and tunnel lining : a review of part and current practices, *Abst. Symp. Rock Mechanics, Ind. Soc. Engg. Geol.,* p. 17.

————————, 1968b—A geological review of the construction and post construction problems anticipated in the crossing of the Krol, Nahan intra-thrust zone by Tons Yamuna tunnel, Yamuna Hydel Project, Stage II,. *Rep. Geol. Surv. Ind.* (Unpublished).

KRISHNASWAMY, V. S., 1967—Geological features controlling the stability of slopes in the vicinity of intake shaft and portal of Ramganga tunnels, Uttar Pradesh, *Rep. Geol. Surv. Ind.* (Unpublished).

MAHENDRA, A. R., 1965—Occurrence and engineering significance of shear zones in the right bank of the Tapti river, Ukai dam site., *Abst. Sympo. River Valley Projects., Ind. Soc. Engg. Geol.*

MATHUR, S.K., and SANGANERIA, J. S., 1968—Geotechnical considerations in selecting the site for under-ground power house, Mahi Hydel Project Rajasthan. *Abst. Symp. River Valley Project., Ind. Soc. Engg. Geol.*, p. 11.

MEHTA, P. N., and DUA, K. J. S, 1965—The Significance of the Krol and Nahan thrust zones to the planning of the Giri-Bata and Yamuna Hydel Schemes, Himachal Prodesh and Uttar Pradesh. *Abst. Symp. River Valley Projects, Ind. Soc. Engg. Geol.*, p. 9.

MEHTA, P. N., and SANGANERIA, J. S., 1965—Geotechnical considerations in the selections of underground power house site for the Yamuna Hydel Scheme, Uttar Pradesh. *Abst. Symp. River Valley Projects, Ind. Soc. Engg. Geol.*, p. 23.

MAKKENJEE, K. K., and ROY, R. K., 1965.—Geological control of groundwater regime in the south eastern part of the Jharia Coalfield in relation to the Panchat reservoir, *Abst. Symp. River Valley Projects., Ind. Soc. Eng. Geol.*, p. 28.

MURTHY, Y. K., and SRINIVASA, B. S., 1965.—Influence of geology on dam design, Abstracts, Symp. River Valley Projects, *Ind. Soc. Engg. Geol.*, p. 21.

NARULA, P. L., 1968—A Geomechanical interpretation of the *in-situ* modulus tests in the exploratory drifts at the Tehri Dam site, Uttar Pradesh *Abst. Rock. Mechanics Symp., Ind. Soc. Engg. Geol.*, p. 3.

NICKELL, P. A., 1945.—Geology of the Bhakra Dam Project, Punjab Govt. Publication.

PANT, G., 1965.—The significance of the epigenetic gorges to the planning of river valley Projects in the Uttarakhand Division, Uttar Pradesh *Symp. River Valley Projects, Ind. Soc. Engg. Geol.*, p. 12.

RAJU, K.C.C., and SHENOY, R. S., 1965.—Influence of geology in the selection of a site for a high dam across Narmada river, Gujarat, *Abst. Ind. Soc. Engg. Geol.*

RAMACHANDRAN, B., and ACHARAYA, A., 1954.—Engineering Geology of the Hirakud dam Project. *Ind. Journ. Pow. Riv. Valley. Dev.*, Vol. IV. No. 10.

RAO, G. S. M., 1965.—Geotechnical aspects of Bihand Dam Project, *Abst. Symp. River Valley Projects., Ind. Soc. Engg. Geol.*

RAO, G. S. M., 1968.—Coarse aggregate for Rihand dam Project, *Journ. Engg. Geol.*, Vol. III, H-1, p. 60-67.

RAO, R. V. S., 1965.—Geology and foundation treatment of Nagarjunasagar dam, Andhra Pradesh. *Symp. River Valley Projects, Ind. Soc. Engg. Geol.*, p. 7.

RAO, V.R. 1965.—Geology and foundation problems at Sholayar and Aliyar dams of P. A. Project, Madras, *Abst. Symp. River Valley Projects, Ind. Soc. Engg. Geol.*

SEN SARMA, S.B., and CHOYDHURY, A.K., 1965.—Geological studies in planning and construction of Jaldhaka Hydel Project, West Bengal, *Abst. Symp. River Valley Projects., Ind. Soc. Engg. Geol.*, p 8.

SESHADRI, R. V., 1968.—Measurement of rock lands, *Abst. Symp. Rock Mech., Ind. Soc. Engg. Geol.* p. 13.

SINGH, V. N., SHARMA, H. D. and SHARMA, M. C., 1968.—Geomechanical criteria and design of tunnel lining for Yamuna Hydel Projects, *Abst. Symp. Rock Mech., Ind. Soc. Engg. Geol.*, p. 9.

SHOME S. K. and DAYAL, H. M., 1966.—On the significance of recent faulting in the Siwaliks to the location of the Majri power House site, Giri Valley Hydel Scheme., *Proc. 3rd Symp. SQk. Engg., Roorkee.*

SHOME, S. K., and DAYAL, H. N., 1968.—Some aspects of tunnelling through the sequeezing ground in the intra-thrust zone of the Giri Bata tunnel. *Abst. Symp. Rock. Mechanics, Ind. Soc. Engg. Geol.*, p. 11.

SHOME, S. K., 1968.—Blasting pattern and overbreaks in the construction of Ichari Chhibro tunnel, Yamuna Hydel Project, *Abst. Symp. Rock Mechanics, Ind. Soc. Engg. Geol.* p. 36.

SRIVASTAVA, A. K., 1965.—Geological studies relating to the alignment of the Pandoh Baggi tunnel, B. S. Link Project, Himachal Pradesh, *Abst. Symp. River Valley Projects, Ind. Soc. Engg. Geol.*, p. 18.

——————, 1968.—Overbreak in relation to the blast pattern and geological features of tunnels 2A and 2B Chineni Hgdel Project, Jammu and Kashmir, *Abst. Symp. Rock Mech., Ind. Soc. Engg. Geol.* p. 24.

SRIVASTAVA, K. N., JAITLE, G. S. and WAZA, J. L., 1965.—Geological factors controlling the location and design of the Pandoh dam and abutment works, B. S. Link Project, *Abst. Symp. River Valley Projects., Ind. Soc. Engg. Geol.*, p. 33.

SRIVASTAVA, K. N., 1968.—Geomechanical analysis of the stability of slopes in the Beas Reservoir area, *Abstracts. Symp. Rock Mech., Ind. Soc. Eng, Geol.*, p. 22.

SUNDARAM, R. K., and RAMACHANDRAN, B., 1966.—Engineering geology of the D. V. C., projects. Abstracts. Symp. Riv. Vall . Proj. in National Planning, *Nat. Inst. Sci. Ind.*

TANDON, G. N., 1966.—Flat jack tests at the site of Chhibro power in house cavity. *Journ. Engg. Geol.*, V. 1. No. 1, p. 33.

——————, 1968.—Stress fields and the design of the power house cavity at Chibro ; Design of pre-stressed anchor for the support of walls of the Chhibro cavity, *Abst. Proc. Symp. Rock. Mech., Ind. Soc. Eng. Geol.*, p. 15-16.

VARMA, R. S., 1962.—Geological studies relating to the seismicity of the Sarpauli Dhikala thrust, Ramganga River Project, Uttar Pradesh Proc, *2nd Symp. Eqk. Engg., Roorkee.*

——————, 1963.—Seismicity of the Kalagarh thrust, *Proc. Symp. Him. Geol.*, G. S. I. (under publication).

VARMA, R.S., ASHRAF, Z. and SENGANERIA, J. S., 1965.—Geological difficulties in planning deep set power houses at the toe of the Ranapratap Sagar and Kota dams, Chambal Valley Hydel Scheme, Rajasthan *Abst, Symp. River Valley Projects, Ind. Soc. Eng, Geol.*

PROBLEMS OF ENGINEERING GEOLOGY IN INDIA

by

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Geomorphological and Geological Set-up in India

Indian rivers are diverse in set-up from rivers of steep gradient and deep gorges within the Himalayas to one of gentler gradient flowing through broad valleys in peneplained country strewn with monadnocks representing relict topography.

The river systems of India in consonance to the topographic expression follow definite courses and can be broadly classified as follows :—

i) Rivers flowing from north in the Himalayas towards south, joining in majority of cases with the Ganga ;

ii) Easterly flowing rivers in the Deccan region originating in Western Ghats and discharging into the Bay of Bengal ;

iii) Westerly flowing rivers discharging into the Arabian sea and originating in Eastern Ghats and

iv) Rivers originating in Central India radiating in all directions.

The contributions of the rivers of the above categories come to 57%, 13%, 14% and 16% respectively to the calculated annual yield of 1,356 m. acre feet.

Problems During the Preliminary Stages of Investigations.

River Valley Projects

Extra-peninsular Region

In the Himalayas the need for regulation of rivers arise from the flood havocs created by them in the populated areas downstream apart from utilising the hydro-power potential. The engineering requirement is to hold an optimum quantity of water in a single reservoir or in a number of reservoirs along the same river so as to hold cumulative quantity. The

extra-peninsular rivers have steep gradients flowing through precipitous gorges, sometimes with a fall of about 125 to 190 m. per kilometer. This makes it necessary to select sites at favourable topographic points offering required spread and volume of reservoir. These are, therefore, very high dams so as to provide projected amount of regulation. The associated difficulty arises immediately about the suitability of rock types, their structure and inherent physical properties to accommodate safely the proposed structures. Even when the rocks are found sufficiently competent to withstand the dam, the seismicity and tectonic history of the area dictate often for a change or rejection of the site altogether. Sometimes both the factors are associated, as is expected in this area having so complex a geological history.

Tista Valley : For the purpose of flood control and power generation here, 4,318 m. cubic metres of water is to be stored for which a site for about 207 m. high dam was considered within the Tista gorge at a site two kilometers upstream, where the river debouches into the plains. The river has a deep canyon with steep walls interrupted by transverse *nalas* having fan-shaped catchment. The location, selected avoiding this factor comprises alternate sandstone and clay-siltstone of Lower Siwaliks, the rocks dipping at 35° to 40° upstream. Though the rock groups are of same age as in Bhakra gorge, they are more micaceous, arkosic and much more crushed. Bhakra rocks showed the crushing loads of sandstone, the stronger member of the rock groups at the site, as varying from 614 to 850 kg./cm^2 in dry state and 526 to 625 kg/cm^2 under saturated conditions. In comparison, the Tista rocks were interpreted to have poor crushing strength. The site was therefore, rejected for a projected 207 m. high dam. A new site, about 23 km. upstream was selected with the Daling group of rocks for a dam of lesser height (Auden 1950, 1951)

Kosi Valley : Kosi, the third largest river in the northern mountain zone of India, maintains an erratic course over the sub-montane tract of silts and sand it had built south of Chatra. There has been a gradual westward swing for over 113 km. between two fixed points at Chatra, the point of exit into the plains and Kursela the point of its confluence with the Ganga. By 1936, some 7,252 sq. km. (2,800 sq. miles) in Bihar and Nepal had been laid bare by floods and silt deposits. To remedy the situation, a series of dams on the tributaries or a single high dam of the order of 227 m. on Kosi below the confluence of the main tributaries, Sun Kosi, Arun and Tamur was considered. This site upstream of Chatra was not favoured because of the submergence of the Barahkshetra temple and because of non-availability of sound foundation rock (the lower Siwalik sandstone, jointed and faulted may not have sufficient bearing

capacity) with the location of the Nahan thrust in the vicinity considered a vulnerable plane of movement in the event of an earthquake. Hence, the site upstream of the Barahkshetra temple, comprising quartzite, sandstones, slates, pseudo-conglomerates and carbonaceous shales of Kosi series was chosen for detailed exploration.

Kishau Dam : A 238 m. high arch dam was proposed across a narrow gorge on the Tons river to augment irrigation supplies and power potential of Yamuna Hydel Project-Part 2, under construction in Uttar Pradesh. The rocks at site comprise Bansa limestone, carbonaceous slates and quartzites of the Mandhali series. The beds dip gently downstream and a number of thrusts dipping at 10° in the upstream direction were met with on the abutment. The abutments rocks are highly jointed with lack of sufficient rock cover on the left abutment, because of bend in the river course. Tests conducted gave very low static modulii values of the order of 0.01 X 10^6 kg/cm^2 (0.20 X 10^6 p.s.i.) in the case of limestone and 0.008 X 10^6 kg/cm^2 (0.12 X 10^6 p.s.i.) for the slates, which showed the rocks to be inelastic in the abutment not capable of withstanding high stresses. A gravity structure also was not found suitable in view of insufficient thickness of limestone at the river-bed level and highly incompetent and sheared nature of the under lying zone of carbonaceous slates, leading to shear failure of the foundations. The construction of a concrete structure in a narrow gorge had, therefore, to be abandoned. An earth and rock-fill structure is now under consideration which could only be built up at an estimated high cost.

Siul Hydel Project : A 122 m. high storage dam was proposed across Siul, a tributary of the Ravi river. The Kalhel limestone taken to be equivalent to Krols proved to be cavernous on exploration. It was estimated that at the proposed head, about 1.27 m^3/sec. (45 cusecs) of reservoir storage will be lost by leakage through the cavities across the Siul river loop. The Project has, therefore be modified into a run-of river scheme.

Peninsular India

In case of dam sites in the Peninsular India the choice of sites are not so rigidly controlled by topographic restrictions, and by the nature and mode of occurrence of rock groups. A little adjustment of locations have resulted in selection of much better alignments. The main problems faced are the depth of overburden in the river section, depth of weathering, and selection of suitable sites for escape structures and reservoir leakage.

Tenughat Dam : At Tenughat, the explorations indicated an overburden of about 15 m. in the river section. Both the banks were, therefore,

investigated for a spillway site. The best site is the right bank, where depth of weathering is less compared to the area around the boundary fault zone on the left bank. The spillway in the river section was ruled out in view of high cost of excavation and other appurtenant protective works necessary for a spillway within the earth dam section. For the obvious reasons of cost, the trend has been towards earth dams with either central or saddle spillway for lengthy alignments in most parts of the Peninsular India, where construction materials are available in plenty. The river sections in general have thick pile of alluvia overlying deep weathered zone. Spillway in river sections require careful design, excavation and elaborate precautionary measures adding to the cost. Where the river sections do not offer suitable sites, spillways are chosen on saddles or on rocky humps-knells characteristic of peneplained areas, requiring elaborate treatment and adjustment of alignments. Interesting cases may be cited from Chandan, Badua and Morwe dams in Bihar, besides the Tenughat already cited and Tikerpara and Balimmela in Orissa.

Badua dam : At Badua, the river flows through a narrow gap within the strike ridges. The 43 m. high dam could not be provided with a conventional spillway within the body of the dam in the river section because of non-availability of suitable foundation rocks. The spillway site was, therefore, selected on the right abutment saddle. After examining the two alternatives of a shaft-cum-tunnel type (glery hole) spillway and chute spillway, the latter was chosen best suited to the topography and rock conditions.

Morwe dam : At Morwe alternating quartzite and phyllite sequence strikes parallel to the river, with quartzites delimiting the valley in north and south. Thick deposits of sand and silt over deeply weathered phyllites cover the valley. The spillway site selected at the northern extremity of the earth dam, would have required 33.5 m. of excavation into the hill and even in that case, heterogeneous formations consisting of phyllites and quartzites, would have formed foundation of the spillway. The alignment of the side channel spillway was placed almost at right angles to the axis of the dam to take advantage of the disposition of quartzites (Sen Sarma).

Hydro-Electric Projects

Topographically the Himalayan valleys with steep gradient, perennial flow, concentration of head along the valley walls and contiguous valley with intervening narrow interfluves offer scope for hydel power development. Storage is needed only to cater the diurnal fluctuation. The main problem

lies in selecting proper type and alignment of the water conductor system along valley wall and often across interfluves. The valley walls, steeply dissected by lateral *nalas*, occupied by thick fluvio-glacial deposits and prone to slides are found unsuitable for locating an open channel or cut-and-cover concrete structures. Tunnels, because of being covered, are favoured for safety as well as for the reason of being untramelled by surface topography. Similar conditions dictated selection of surge shaft and pressure tunnel instead of open contour channel and forebay combination at Jaldhaka, as conceived earlier. The valley walls here are constituted of terrace gravel—boulder deposit of enormous thickness and having been effected by landslides was considered unsuitable for a contour power channel (Hazra, 1962).

Problems Related to The Foundation Rocks

In India the complex geological history of the rock formations has resulted in complete or partial loss and transformations of the initial characters. The effect of the climate on the rock mass makes it more complicated, the formulation of design of a structure and its ultimate stability. The suitability of the foundation rocks is guided broadly by the (a) fundamental intrinsic properties of the lithological units including physical properties such as compressive strength, elastic properties, resistance to abrasion *etc.* (b) response of the rocks to the various forces, induced during construction of structures. The predominantly controlling factors are the (*i*) tectonic forces imposing divisional planes within them (*ii*) changes brought about by the exogenic forces or physico-meteorological process and (*iii*) changes due to endogenic forces or hydro-geochemical processes.

All these factors are manifested in the shearing, slump cracks and capricious weathering including solution channels, cavities and tunnels in calcareous formation. The attitude and extent of distribution of these features influence to a great extent the final design or remedial measures for structures.

The effects of these features are (*i*) seepage through foundation rocks, resulting in uplift pressure on the structures. This may take place competent and brittle rock groups rendered by intense jointing permeable nature of altered and weathered rock units and through well defined fault planes acting as channels allowing copious flow through them, (*ii*) inequality of foundation strength and compressibility at different points of the foundation. Alternate, competent and incompetent rock formations are also responsible for the heterogeneity and (*iii*) the attitudes of the rocks and divisional planes being so disposed as to favour sliding. Shear planes traversing the foundation rocks at low angle and without lateral rock restraint are commonly observed in foundation and abutments.

At Bhakra, the gravity dam (225 m. high) is located across Sutlej river on the Lower Siwalik sandstones interbedded with clay stones and siltstones. The major problems at Bhakra related to uniform stress distribution foundation members having contrasted modulii of elasticity, shear and settlement of the abutments along cross shear zones, control of leakage and uplift pressures and, stability of the slope cuts. These were resolved by consolidation and curtain grouting, shear keys, formulae trenching raft foundations and rock anchoring.

In Hirakud Dam, the problem related to the existence of (*i*) cross fault running across the dam axis in block 54 with a 4.5 m. wide crushed zone along the fault plane having 0.6 to 1.5 m. thick clay gauge. Heavy seepage was present along the plane. Phyllite, slates and ribs of quartzites were highly jointed and the average loss of water in boreholes noticed was over nine l.p.m.

A strike fault with wide crushed rock gouge traverses through the central part of the foundation constituted of phyllites, quartzites with intrusive meta-dolerites at Barapani Dam, Assam. The rocks are jointed with the the foliation dipping downstream.

At Chandan Dam, Bihar composite gneisses, alternating with amphibolite and granulite and traversed by pegmatite veins constitute the foundation rocks of the spillway. The weathering is capricious and selective. Fiesh rocks occur at depth of 14 m. or below. A pegmatite vein 4 to 9 m. thick runs across the axis of the spillway in a deeply weathered state.

These above mentioned features, necessitated elaborate treatment of the weak planes by way of grouting, providing shear keys, selective excavation and back filling with concrete, providing drainage galleries, and combining constructional blocks, thereby providing wider surface contacts and distribution of stress, besides deeper excavation to get fresh rock grade.

Problem of Reservoir Leakage

Escape of stored water in the reservoir is effected either through permeable formations of the reservoir area or through topographic gaps. The latter is easily recognisable during land survey while detailed studies are necessary for the former one. The problems are highlighted in some of the cases are discussed below :

The Moosakhand Dam site in Uttar Prádesh is located across Karamnasa river S. E. of Varanasi. The hills in the area comprise gently dipping Kaimur

sandstones, with older alluvium in the plains. Buried channels were proved by geophysical survey to lie transverse to the dam axis on the left bank and extending below the foundation of the completed earthen dam. Exploratory drilling proved presence of highly pervious till material in the channels overlain by peaty clays. Later, on impoundment of the reservoir, the burried channels got connected with the reservoir and considerable seepage under artesian head was recorded in observation hole at the toe of the dam. To control piping below the dam foundations, a battery of relief wells have been planned across the burried channel and at the toe of the dam to lower the peizometric head.

Panchet Reservoir, D. V. C., Bihar : The problem of water flooding in coal mines along the periphery of the Panchet reservoir was investigated in connection with the question of compensation to the mine owners. The reservoir area is occupied by Pre-Cambrian granites and Gondwana shales and sandstones. The behaviour and disposition of the water table and its relation to the aquifar and permeability of the rocks were studied. Groundwater occurs under water table condition in the saturated zone of the overlying alluvium and the hard rock. The water table was found to maintain (*i*) broad conformity with topographic features and with a gradient of 25 m. per km. to 5 m. per km. towards the reservoir and the slope of water table downstream of the dam was found parallel to the river flow. The conclusions drawn are (*a*) the slope of water table indicated no possibility of seepage from the reservoir, in the adjacent coal mines due to the affluent condition of the reservoir, (*b*) The geological formations including the shales and sandstones by virtue of their impervious character and back of prominent divisional planes act as barrier to groundwater flow and (*c*) observations in the adjacent coal mines bear out support to the above conclusions.

Mula dam, Maharastra : A 45.72 m. high earth dam has been completed across Mula stream, a tributary of the Godavari river. At the site the Deccan traps have been deeply weathered and the flanks are covered with 9.14 m. deep river deposits. Three prominent horizons of bole beds of the order of 1.5 to 3.04 m. and the high degree of weathering necessitated deep cut-off trenches to protect the bole beds from deterioration. As the grouting of the alluvial deposits was not successful a concrete diaphragm had to be provided.

Obra Dam, Mirzapur district, Uttar Pradesh : The earth dam, under construction across Rihand river lies 32 km. downstream of Rihand Dam. The project area comprises highly cavernous and altered Vindhyan limestone and carbonaceous shales. The Vindhyans are folded synelincally plunging towards the Son river with a faulted contact towards the south

with the Bijawars. Sandy overburden of 24 m. thickness was proved in the river section with a 46 m. deep buried fall extending downstream along the river, probebly coinciding with the fault zone. The problems are control of reservoir leakage through the cavernous limestone towards the Son river and treatment of weathered and cavernous limestone in the foundations of the right spillway. The foundation problems were solved by curtain and consolidation grouting aligning the cut-off along carbonaceous shales and providing a grouted diaphragm tied down to bed rock in the river section.

Meja dam district, Mirzapur, Uttar Pradesh: The dam has been constructed across the river Belan on the Kaimur plateau. Exploration in the river section proved an overburden of about 21 m. The material comprised a top zone of sand and gravels underlain by peaty clays and fluvio glacial debris. The permeability of the fluvio glacial material was found to be of the order of 10^{-5} to 10^{-6} cm/sec. To control seepage and piping, the peaty clays were removed from the foundations, three miters deep core trench with clay cut-off was tied down into the fluvio-glacial debris and relief holes were provided at the toe of the dam.

Tunnels and Underground Excavations

Major tunnelling Projects have been taken up in the Indian subcontinent only during the post-Independence period. The selection of a proper alignment is of primary importance for building a safe and economic tunnel. Sub-surface exploration for dalineation of weak rock zones and assessment of portal conditions and rock cover are undertaken for advance modifications of the alignment chosen, among the many alternatives examined

Jawahar Tunnel Project in Jammu and Kashmir and the Beas-Sutlej Link Project in Himachal Pradesh can be mentioned where a number of tunnel alignments were geologically examined and explored before a final choice was made. At the Jamuna Hydel Project and Giri Hydel Project, the tunnel alignments had to be curved in order to reduce the thickness of the squeezing ground likely to be met within the Intra-Thrust zone (formed of older Tertiaries lying in between the Krol and Nahan Thrusts).

The problems encountered involve excavation through weak flowing and squeezing rock zones with high hydrostatic heads, seismically active fault zones, and design of temporary and permanent supports. Lack of data on rock pressures and rate of creep along fault zones makes the design of permanent lining supports extremely complex. Now only an empirical approach is being followed guided by the work carried out by K. Terzaghi and *in situ* modulus of elasticity and deformation tests.

Generally the concrete lining thickness is kept constant as far as possible while the spacing of the steel supports is only altered to meet the variation in external rock loads. Heavy hydrostatic pressures on tunnels linings are relieved by drainage holes. For high internal heads in pressure tunnels where rock deformation is anticipated ; similarly, increase in the re-inforcement is attempted without altering the lining thickness.

The Intra-Thrust zone with squeezing ground under probable tectonic stresses has to be intersected in tunnelling at Giri and Yamuna Hydel projects. Exploration by means of drill holes and drifts have indicated the crushed gougy rock zone to be under a stress of about 500 p.s.i. (35 kg/sq. cm). Drifts have indicated bodily movement, tilting of timber supports and plastic flow of clay gouge around steel ribs. Load cells and dial gauges are being installed in the drifts to determine the stresses and the rate of creep movement. Rock deformation tests by means of Radial Press have also been conducted for a quantitative study of the behaviour of the squeeging rock zones for the tunnel lining.

During tunnel excavation major collapse and blow-outs occurred at the Beas-Sutlej Link project, Himachal Pradesh in crushed rock zones charged under high hydrostatic pressures, lying within the extension of Dhauladher quartzites, limestone and dolomites of the Shali series. The blow-out hydrostatic pressures at the tunnel heading were estimated to be of the order of 100 to 300 p.s.i. Flowing ground was encountered in the crushed quartzites on account of lack of cohesion and extremely poor coefficient of internal friction which on being recharged by groundwater behaved like quicksand and flowed into the tunnel. Remedial measures like drainage of the cavity section, grouting and forepoling had to be adopted to advance through these reaches.

The existence of a filled up valley along a fault zone favourable for the accumulation of groundwater in the interconnection tunnel between Avalanche and Emerald reservoirs of the Kundah Hydro-electric project was indicated from the geological studies carried out. During driving the tunnel, there was a sudden rush of water and sand near about Ch. 3,171 with the formation of a 36.6 m. wide and 15.2 m. deep depression at about 30 m. above the tunnel grade. The tunnel floor was depressed between Ch. 2,890 and Ch. 3,220 with a gradient of 1 in 4 so as to be within firm rock.

Stability of Hill Slopes

The topography in the Himalayas is immature, slopes are normally steep, and weathering is deep. Over all morphology bears the evidence of tectonic stress release. In the dynamic cycle of the evolution of slope,

the Himalayan landscape presents inequilibrium condition. The expression of failure differs topically from place to place because of the predominance of one or other of the elements causing it. But the study of the hill slopes around Dalhousie, Simla, Nainital and Darjeeling paints out to certain common features. These are (*i*) the geometric patterns of the slopes are indicative of unstable condition in the context of slope evolution ; (*ii*) the townships often extend to areas occupied by debris accumulation from earlier landslides ; (*iii*) thick mantle of weathered rock is easily affected by the interaction of climatic elements, and (*iv*) drainages for run-off provided are invariably inadequate.

In some cases, it has been possible to assign the cause of instability of the slope in quantitative manner, but the main problem still remains to ascertain the quantitative values of the parameters responsible for causing slide. One of the methods used was to analyse the slope characteristics and correlating it with the geological characters. The status of the different segments of slope in its evolutionary history has been attempted. At Nainital, measurements of slope translation has established the rate and direction of movement. The properties of rocks and slope wash materials, ofter responsible in causing landslide have been qualitatively ascertained only. The remedial measures require elaborate and expensive structures. In most cases assessment of the utility of the suggested measures could not be made in post-construction stage.

Road Alignments

Roads extending to hundreds of kilometres have been built and are proposed to be constructed to open up unexplored areas in the Himalayas and to connect the hill towns and other important localities. Since the approach is from foot hills towards further north, these roads have necessirily to negotiate ascending and rugged topography and also unfavourable structural and lithological units. It is not always feasible to align the roads normal to the structural grain and attitudes of rock units. Avoidance and circumventing of unfavourable zones are not possible always. It is not possible to eliminate natural hindrances entirely. So there are bound to be sections where trouble will continue to occur. The most severe problem in the course of investigation for selecting road alignment emerged out to be landslides of various types, nature, dimension and frequency along road lengths. This takes the geologist into the detailed studies about the cause of the origin of landslides and subsidence and thereby evolve remedial methods. Various types of landslides such as rotational slide, block gliding, subsidence, creep, rock slide *etc.* have been identified.

The nature and extent of weathering of rocks forming the outer shell of the mountain mass over which the roads are aligned, their physical

properties, the role of groundwater and the structure of surface rocks need careful assessment for correct and quantitative evaluation of the landslides. Measurement of the time-rate of the movement picture by instrumentation is needed to minimise the gap in the study so far done on predominantly visual observation.

Engineering Seismology

The cause and effect of earthquakes have been the subject of intensive studies from the early days of the Geological Survey of India. But the particular phases of seismology, related to the design of structure were taken up as subject of special study by the Engineering Geology branch much later. The need rose out of the question of construction of high dams in the Himalayas and also in the Damodar Valley. Question was raised regarding the possibility of Damodar basins being the focus of earthquake shocks of heighest magnitude.

This aspect projects the problem into the field of dynamics where data regarding the ground vibration associated with earthquake shocks along with the analytical techniques associated with forced vibration are sought for.

The studies have mostly been non-instrumental. Areas subjected to earthquakes damages have been ascribed certain values representative of the intensity of earthquakes corresponding to intensity scales based on the destructiveness of man made structures. Geological features and geomorphic units have been studied for ascertaining probable deformation or dislocation during the earthquakes. This has proved regionalisation of earthquake areas within mobile crustal blocks, which are the loci of epicentres of earthquakes of variable magnitudes during the last 110 years.

Certain pertinent conclusions arrived at by these studies are of interest. The geological features in comparison of the gravity anomaly map of India and the map woth the plots of past earthquake epicentres have enabled delineation of the seismic zones. Major earthquakes have originated in Montene zones itself and close to Himalayan frontal areas.

The thrust planes between the formation of different geological age were subjects of special studies, regarding their seismic activity. Studies based on geological evidence have only been made to prove whether these planes showed any sign of movement during earthquakes. Seismic instability appears to be connected with tectonic features lying to the south partly concealed below Gangetic alluvium and partly connected with Shilong plateau and Aravalli-Delhi promontory. The studies have been statistical and have enabled to assign values for seismic safety factors for

a seismic design of dams and other structures for different projects. Seismic studies so far made even with the quantitative values representative of the earthquake intensities, is still descriptive. Evaluation of the magnitude, ground acceleration, relation of epicentral distances with the ground vibration through crustal blocks of varying mobility, and the behaviour of structure in the field of forced vibration are yet to be undertaken. This is possible only from instrumental data and with a network of seismic observatories spread throughout India. The delineation of crustal blocks of different mobility is a guide to the probable locations of these centres.

Conclusions

So long an attempt has been made to enumerate some of the problems connected with various engineering constructions. A brief mention is made of the future scope of studies in different related fields.

The problems that have been reviewed fall under the following broad branches :—

(*a*) *Geomorphology*—Detailed study is called for chiefly in relation to the limitations imposed upon by topograpghy in the choice of development schemes, particularly in Himalayan terrain. This aspect has been studied sporadically and more intensive study needs greater emphasis. The morphometry of a region in so far as its status in the evolutionary history of the landform is concerned indicates several factors connected to the choice of investigation methods. Peneplaination history, evolution of slopes, and basin characteristics recognisable in quasi-quantitative terms by advanced and up-to-date geomorphological analysis obviates irrational approach to engineering problems. Its role in the assessment of siltation problems in reservoirs when studied in conjunction with the geological set up needs no special emphasis. It has been demonstrated by calculating the rate and amount of siltation in north-western Himalayan river basins after incorporation of these parameters to the common formulae, the results corroborate with the observed amount more closely than those obtained by formulae.

(*b*) *Rock and soil mechanics :* The foundation problems relate mostly to the intrinsic rock properties and the behaviour of rocks in the existing stress field of the earth and under induced pressure. The settlement of foundation rocks, distribution of stress around underground openings and connected failure, slope translation, rock comminution by drilling or blasting and even the large scale deformation by folding and faulting are all amenable to analysis from a mechanical view point though there is wide misconception about the applicability of the existing knowledge of mechanics and allied branches to rocks which lack homogeneity and

are not ideally elastic. The study, is determination with mathematical precision the indeterminate parameters.

In fact, it pertains to the analysis of the behaviour of a unit rock block in laboratory conditions and the same by rocks with a series of discontinuities in a wider scale in the field under different state of stress. The purpose is to bridge the schism existing between the empirical analyses commonly used and the required precision. The scope of this field of study is vast and the need for it is more apparently brought out recently in the controversy about the behaviour of reservoir rocks under the pressure of vast column of water in Koyna reservoir in so far as it is related to and responsible for the origin of earthquake by failure of rocks.

(*c*) *Foundation treatment* : Most widely applicable method of treatment for different kinds of foundation defects is by grouting. But the method still is in its embryonic stage in the sense that the different parameters and variables connected with the process have still not been precisely determined. The treatment is by trial and error method in all the related aspects - *viz* the correlation of permeability with grout intake, effective pressure of grouting, radius of influence of grouting, suitability of grout meterial used *etc.* There is also wide scope for quantitative evaluation of these factors.

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References

ACHARYA, A. and RAMACHANDRA, B. (1954) — Engineering Geology of Hirakud dam project. *Indian Jour. of Power & River Valley Development Hirakud Number.*

AUDEN, J. B. (1951) — Bearing of geology in multipurpose Projects. Presidential address, *Indian Science Cong,* Section 5.

———— (1950) — The role of geology in multipurpose Projects. *Proc. Nat. Inst. Sci.,* Vol. 16, No. 6.

DUTTA, G. N. (1950) — Geological aspects of North Bengal floods—*Indian Jou of Power & River Valley Development*—West Bengal, *Power & Water resources Volume.*

DUTTA, K. K. (1952) — Sub-surface exploration at dam sites. *Indian Minerals.* Vol. 6, No. 1.

HAZRA, P. C. and DUTTA, K. K. (1961) — Geological investigations of dam sites. *Indian Minerals,* Vol. 15, No. 2.

HAMZAH ALI and others (1962) — The role of the Geological Survey of India in irrigation and power projects. Indian *Mineral,* Vol. 16, No. 3.

HAZRA, P. C. and RAY, D. K. (1962) — A short note on seismic phenomena in India and their relation to tectonics. *Indian Minerals,* Vol. 16, No. 3.

MUKHERJEE K. K. (1968) — A report on the investigation of seepare from the Panchet Reservoir into the adjecent Coal mines of Jharia Coal Field, Bihar, *Rep. Geol. Surv. Ind.*—(unpublished).

SUBRATA SINHA and MUKHERJEE, K. K. (1965) — A note on the progress of geohydrological investigations in the areas bordering Panchet Reservoir, Dhanbad and Purulia districts *Rep. Geol. Surv. Ind.* (unpublished)

RAJU, K. C. C. (1967) — Studies in the stability of the northern part of Simla—*Jour. of Eng. Geol, Vol,* II., *No.* 1.

SEN SARMA S. B. (1963) — Potentialities of the hydel power development in the district of Darjeeling, West Bengal—Indian *Journal* of *Power & River* Valley Development (West Bengal Power Volume).

SEN SARMA S. B. and RAY SUKANTA. (1967) — Application of slope analysis to the problem of landslide investigation—*Jour. Eng. Geol,* Vol. II. No. 1.

ENGINEERING GEOLOGICAL PROBLEMS IN HARD ROCK AREAS

by

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Introduction

The Peninsular shield occupies about two-thirds of the Indian Union from Cape Comorin in the South to Rajasthan, Madhya Pradesh, and Bihar in the north. The shield continues below the Gangetic alluvium to the Shillong plateau of Assam in the east. In this vast expanse occur the rocks of pre-Cambrian, Gondwana and Deccan Traps and coastal Tertiary sediments. Barring the Gondwanas and the Tertiaries, the rest of the area is composed of the hard rock formations.

Geomorphology of the Peninsula

The Peninsula represents an ancient denuded plateau. The Western and Eastern ghats, Vindhyans, Satpuras and the Aravallis are the important hill ranges of it. The Aravallis are considered to be of tectonic origin, while the rest belong to the relict type.

Broadly speaking there are two major watersheds in the Peninsula; the Central Indian Plateau comprising the Vindhyan and Satpura ranges, and the Western Ghats. From the Central India Plateau, flow the Chambal and the Son to the North, the Damodar and Subarnarekha to the East, the Wainganga and Wardha to the South and the Tapti and Narmada to the West. The Godavari, Krishna and Cauvery originate from Western Ghats flowing across the width of the Peninsula. The Vaitrana, Kalahandi, Kalanadi, Bedthi-Gangavali, Sharavathy, Varshi, Aghnesini, Netravathi, Chalakudy, Perambikulam, Kunnai, Periyar and Kallada are some of the west flowing rivers, which have their origin in Western Ghats. The Mahanadi and Indravati rise in the Eastern Ghats, former flows directly into Bay of Bengal and the latter joins the Godavari.

Unlike the east flowing rivers of the Peninsula, the rivers having their origin in the Western Ghats, flow for short distance of 150—300 km. through mountainous terrain and join the Arabian sea. They drain an area of heavy rainfall, but carry comparatively less volume of water. They

have not built up any major deltaic plains. These rivers, still in their youthful stage have immense hydro-power potential. Major hydro-electric projects like the Sharavathy, Iddiki and Kalinadi are located in these valleys.

The geomorphology of these river basins has a direct bearing in the planning of the projects. The easterly tilting of the table land of the Peninsula, the Gondwana trough and the west coast faulting and the uplift of the Eastern Ghats have all left their impression on the morphological history of the Peninsular rivers. The Damodar, Son and Mahanadi valleys are bounded by faults. Their E.—W. to E.N.E.—W.S.W. course are either parallel or slightly oblique to the foliation strike of the rocks. The Narmada and Tapti follow straight faulted courses. The Godavari, after receiving Pranwita, one of its major tributaries, changes its course to south-east and flows along the Gondwana rift. Many of the river courses in the States of Madras and Kerala lie along fault or shear zones, whose trends are generally parallel to the west coast fault. The rejuvenation of the Godavari, Krishna and Penner consequent to or contemporaneous with the uplift of the Eastern Ghats is responsible for their deep gorges. These gorges, exposing hard rock now provide suitable sites for the construction of large storage dams, which are essential for the impounding the seasonal flows in these rivers, at the tail end of their courses. The undulating table land lying in between the Western and the Eastern Ghats and its low relief result in construction of very long structures. Yet, one more geomorphic features of importance is river privacy observed in some of the west flowing rivers like Sharavathy, which endowed the valleys with huge hydro-power potential for economic utilisation.

Structure and Tectonic History

The three major lineations readily discernible in the rocks of the shield are the N.E.—S.E. strike of the Aravalli and Eastern Ghats, the N.W.—S.W. strike of the Aravalli and the Eastern Ghats, the N.W.—S.E. or N.N.W.—S. S.E. strike of Dharwar and Mahanadi and the E.N.E.—W.S.W. Satpura strike. The major rift valleys of Narmada and Godavari have E.—W. and N.W.—S.E. lineations. In the Nilgiri and other West Coast areas, major shear zones show N.—S. trend. The concave eastern margin of the Cuddapah basin is highly disturbed and folded. The repeated intrusive activity witnessed in the early pre-Cambrian period brought in its wake shearing and crushing of the associated rocks. These constitute some of the major structural discontinuities of the Peninsula.

Problems in Hard Rock Areas and their Treatment

Engineering properties of rocks

The Peninsular shield consists of all the three groups of rocks, igneous,

sedimentary, extrusive and their metamorphic equivalents represented by pre-Cambrian and Deccan Trap formations. Granites, granodiorites, gneisses, chamockites, dolorites, schists, massive and amygdaloidal basalts, quartzites, crystalline limestones, slates and shales are the common rock units found in the hard rock area. Barring some varieties of schists, slates and shales, the remaining rock types possess high strength and provide good foundations and constructions material for civil engineering works.

Engineering properties of many of the rock types occurring at various dam sites in India are given in Table—1. (compiled from G.S.I. unpublished reports).

These results indicate the strength of individual rock samples. The characteristics of the rock masses as a whole, may vary considerably depending on the degree of fracturing, jointing and weathering. The rocks of the same unit, belonging to different geological ages or formations differ widely in their engineering properties depending on the residual stresses and their geological history. Again, the individual values obtained for any rock mass or sample depend on the type and mode of testing.

Foundation problems

The suitability of the foundation material depends on (i) its intrinsic strength as measured by its compressive and shear strength and elastic modulus, (ii) the degree and extent of the mechanical discontinuities existing in the rock mass, (iii) its degree of weathering, alteration and decomposition, and (iv) its response and behaviour to imposed stress conditions. Naturally, in the hard rock areas, which encompass wide range of rock types with varied and complex geological histories, diverse problems of different magnitudes can be expected and encountered. Under these limitations, some of the problems more frequently met with in these areas are :—

1) problems related to weathering including solution cavities and channels.

2) problems of jointing and fracturing.

3) problems connected with faults and shear zones.

4) problems connected with layered formations, including the occurrence of alternating sequence of competent and incompetent rocks.

Problems of weathering

In the Peninsular shield which represents and ancient plateau, weathering of the rocks is a common feature. The intensity and extent of

weathering, however, differs widely, depending on the formation characteristics and the physico-chemical process at work.

In the Western Ghats region, weathering and decomposition has extended to depths as much as 30 to 50 m. Weathering may be restricted to one of the abutments or flanks only. In some other cases weathering and decomposition on the abutments might extend even below the general river bed level. The case histories of Sharavathi valley and Kalindai projects illustrate these problems.

Selective weathering is characteristic of foliated and layered rocks offering differential resistance to weathering. In the Eastern Ghat region where hard charnockite or pyroxene-gneisses and softer felspathic gneisses or graphite-schists occur interbanded, the latter are susceptible to deep weathering. Investigations in these regions have to be directed towards delineation of weathered zones and aligning the structures on hard rock bands. Deep excavation, spreading of the foundations and transfering of loads on to hard rock ribs are the general remedial measures adopted. Such problems have been encountered at many project sites like Sabargiri Kulamavu in Kerala, and Lower Sileru in Andhra Pradesh.

In crystalline igneous rocks, coarse-grained varieties show greater susceptibility to weathering than the fine-grained varieties. Spheroidal weathering is common in massive rocks like granites, charnockites and dolerites. The continuity of fresh rock to sufficient depth below the general foundation grade has to be proved to avoid surprises during construction.

Weathering may be pronounced along contacts of different rocks, bedding planes, joints and faulted and shear zones, requiring through investigation.

Some of the carbonate rocks, particularly dolomitic and siliceous limestones occurring in areas of humid climate with high water table, are to be examined for location of cavernous zones.

Joints and fractures

The most common problem in the massive formations like granite, charnockites and basalts is the presence of secondary features vitiating their monolithic and near isotropic character. They may occur in regular patterns as columnar jointing in basalts, or have random orientation as in granites. Basal sheet joints, often parallel to the topography are common in granite and charnockites. Many of these joints, open at the surface, tend to close with depth and become fairly tight.

Under the dam foundations, these permit leakage and build up uplift pressures, besides facilitating decay of the rock. In tunnels, these leads to serious roof falls and considerable over break. In the deep cuts or along steep slopes, their adverse disposition aided by the lubrication provided by saturated infilling material may give rise to rock-slips and landslides.

Study of joint and fracture patterns, the degree of opening and their extent, and nature of material along the joint planes become essential for planning grouting patterns and choice of grout mix. Different types of rock belting are adopted in tunnels and deep cuts to prevent rock falls.

Faults and shear zones

The predominant problem relating to foundations in the Peninsula is faults and shear zones. Their extension in lateral and vertical directions vary between wide limits. Sometimes as at Hidkal dam site, the fault zone has the same width, even at 30 m. depth. The rocks in these zones are generally highly crushed, altered, and decomposed and mixed with clay and gauge material. They form well defined weak zones; afford channels for seepage; and cause differential settlement, needing suitable measures to counteract them.

Problems connected with layered rocks

The metamorphic rocks, the pre-Cambrian sedimentaties, and Deccan traps are mainly represented under this group.

In the metamorphic rocks, the foliation forms one of the important planes along which the rocks are weaker and more susceptible for decay. Generally, these are tightly folded and occasionally faulted. Brecciation and excessive fracturing are associated with these rocks. Presence of large quantities of mica and vermiculite render some of the schistose rocks unsuitable as foundation material.

The common problems encountered in the pre-Cambrian sedimentary rocks are (i) block jointing, (ii) presence of soft interbedded shales and (iii) presence of clay along bedding planes. Jointing requires extensive consolidation grouting to render the rocks monolithic. The incompetent interbedded shales and the thin clay seams along the bedding planes give rise to problems of sliding besides differential settlement in the horizontally bedded sedimentary formations. Hence shear strength (C) and the sliding friction (tan θ) by *in situ* testing are determined. Mobilisation of frictional resistance of the side rock by suitable excavation, keying of the structure sufficiently deep into the rock, and provision of anchor blocks are some of the measures commonly adopted to solve the sliding problem.

The Srisailam hydro-electric project under construction illustrates these problems.

In the case of Deccan traps, massive basalt flows are underlain or overlain by softer breccia, amygdalodial flows or red bole. These present specific problems in evaluation of foundation grades and foundation settlement. The case history of Koyna dam exemplify these problems.

Foundation treatment

Numerous methods of treatment have been adopted depending on problems and site conditions. Excavation of the soft and crushed material to twice the width in narrow shear or fault zone, or to the depth indicated by photo-elastic tests in wide zones are most common of all foundation treatments. A sufficiently deep shaft is provided on the upstream to serve as a cut-off and to reduce seepage through the zone. A similar shaft, but extending to lesser depth is provided near the downstream to confine the soft material if removal of "Fines" is suspected. Provision of an R.C.C. mat or raft over the soft zone to prevent differential settlement and transfer of the loads to shoulder rock are also generally adopted. In some instances additional drainage galleries are provided over these zones to relieve uplift pressure. Seams of weak material occurring beneath sufficiently thick cover of sound rock are often mined or scooped out, without disturbing or removal of the overlying rock.

Grouting of the foundations, abutments, shear and fault zones and tunnels for reducing seepage, consolidation and stabilisation is a common practice.

The pattern and method of grouting, choice of grout material and the consistency of grout mix all depend on the formation characteristics, disposition of the divisional planes and the purpose of grouting. A detailed study of the joint pattern, and their openness as determined by water tests, help in the formulation of suitable grouting pattern. Thorough washing of the material filling the joints is conducive for effective grouting. The effectiveness of grouting is checked by drilling test holes in the grouted area and repeating the water tests. The ratio, the volume of grout intake bears to the statistically weighted joint-void space serves as a good index of the effectiveness of grouting, provided there had been no serious loss of grout through surface and other leakage. In certain cases where consolidation of the formation is aimed at as in the case of abutments of an arch dam, the grouting operations are repeated until the desired modulus of elasticity values are realised.

One of the measures enumerated above or all of them may be employed

for the treatment of the foundations, based on the complexity of the problem. The case histories of projects illustrate the major problems encountered and their solution.

Case Histories

The case histories presented in this chapter are broadly arranged in the following order—those falling in (1) Dharwar and Archaean terrain, (2) Cuddapah and Vindhyan formations, and (3) Deccan Traps.

Sharavathy project (Mysore State)

The Sharavathy Project provides an example of problems posed by deep weathering. Granite gneisses, amphibolite schists intruded by granites, dolerite dykes and pegmatite are the major rock types of the area. The general strike of foliation is N.W.—S.E. and cross folding has been recorded. Faults of minor magnitude trending parallel to the foliation were exposed by excavation in the river bed.

At the 54.26 m. high Linganamakhi dam site, massive hornblende schist on the left abutment, granite gneiss in the river bed and pink clayey talcose material extending to 20 m. depth on the right flank are the main features. A rock fill dam with central impervious core had been constructed on the right flank. The anchor for some of the penstock pipes had to be taken down to 33 m. depth through pile foundations.

Kalahandi hydro-electric project (Mysore State)

Banded magnetite-haematite-quartzite associated with bands of siliceous and ankeritic limestone and dolerite dykes occur at the Supa gorge site. They trend in N.23°W.—S.23°E. and at the dam site dip towards downstream. These form a part of the regional folding, and the major structure at the dam site is an asymmetrical anticlinal fold pitching into the left abutment. The right abutment presents a 12 m. long cave associated with ankeritic limestone at the river bed level.

Over 3,000 m. of exploratory drilling and over 1,000 m. length of drifting were carried out to examine the abutment conditions. The decay of the rocks on the abutments extend to the river bed level and below. The rocks exposed in the river bed are fresh and reasonably tight. A few zones of "no core or poor core recovery", indicative of solution cavities or intensely decomposed rock were met with in the boreholes at different depths. These are restricted in their extent with no interconnection between them. "*In situ*" tests to determine the compressive and shear strengths of the rocks, experimental grouting and water tests are under progress.

Exploratory drilling at the Nagjheri Power House site revealed a 60—90 m. deep fill material and the presence of buried old river course near the foot of the hill. An alternate alignment on sound rock has been selected.

Idikki hydro-electric project (Kerala)

The Idikki hydro-electric project consists of the 137 m. high Idikki arch dam 129 m. high Cheruthoni concrete dam, and 72 m. high Kulamavu masonry dam.

The steep and narrow 215 m. deep gorge with a chord height ratio of less than 2 :1, with massive charnockite over the entire abutments and river bed, presents an ideal site for the high arch dam.

More than 1,900 m. length of core drilling and 250 m. length of exploratory drifting were done to examine joint and fracture patterns on the abutment. (The 'E'—value of the charnockites was found to range from 2.5 to 5.0 $x10^6$ p.s.i. by *in situ* testing).

Charnockites and granite gneisses from the right and the left flanks foundations respectively at Cheruthoni site. Depth of excavation to the foundation grade varied from 6 to 12 m.

At Kulamavu site granite gneisses, pegmatites and graphite-schists comprise the foundation. A four metre wide shear zone was encountered in the river bed associated with the graphite-schist, and delineated by extensive drilling. Three shafts one on the upstream and the other at the toe with a middle observation shaft were provided. A nine metre thick concrete mat has been provided over the soft zone in addition to the grouting treatment.

Kuttiyadi hydro-electric project (Kerala)

At the 40 m. high Kuttiyadi dam site, granite-gneiss and amphibolites are the foundation rocks. The main foundation problems are selective deep weathering on the left flank, the presence of a 4 to 6 m. wide shear zone in the river at the junction of the amphibolites and the gneisses and the instability of the left abutment.

Exploratory drilling indicated excavation to be 40 m. on the left flank. The shear zone in the river bed follows the foliation of the gneisses extending from upstream to downstream, comprising crushed gneisses and amphibolites. This was excavated to twice its width and back filled with concrete. Consolidation grouting extending to eight metres below the excavation grade was carried out.

The peculiar configuration of the left flank gives rise to a narrow tongue of the reservoir extending downstream of the left abutment hill partially encircling it. Seepage through the deeply weathered zone endangering the ultimate stability of the left abutment hill is involved. Grouting of the soil and weathered rock, provision of an impervious blanket on the upstream and a 91 m. long drainage adit into left abutment hill are the measures contemplated.

Parambikulam-Aliyar project, (Tamil Nadu)

Parambikulam-Aliyar project consists of eight dams and three power houses and appurtenant structures like contour canals and tunnels.

Biotite-gneiss, charnockite, granulite and leptynite are the chief rock types of the area. The gneisses are foliated N.N.E-W.S.W. The regional drainage as well as the major shear zones are aligned parallel to the foliation direction of the gneisses. The depth of weathering ranges from 9 to 22 m.

At the 73 m. high Parambikulam dam a 3 m. wide shear zone associated with pink granite and pegmatite, trending in N.45°W.-S45°E. and dipping vertically was encountered in the river bed. Excavation to twice the width, provision of 7.5 m. deep cut-off trench on the upstream, grouting of the shear zone and a transverse gallery over it were the treatment measures adopted.

At the 105 m. high Sholiyar dam, a shear zone in the river bed was excavated to 18 m. depth. A transverse gallery was provided over the fault zone, which was grouted.

The deep weathering of granites extending to 20 m. depth on the right flank led to the change of the original alignment and the design from masonry to an earth section on this flank, during construction stage.

The spillway of the 71 m. high Aliyar dam was founded on jointed granites, requiring considerable foundation treatment by way of cement grouting during and after construction to achieve water tightness.

Balimela project (Orissa)

The principal rock types of the project area are khondalite, charnockite with associated rock types, and biotite-gneiss. Their foliation trend is N.E.—S.W. with steep dips towards south-east. Minor shear zones in the area trend parallel to the foliation. At the site for the 74 m. high earth dam across Sileru river weathering extended to 55 m. depth in khon-

dalites on the left bank and 26 m. depth in charnockites at the proposed spillway location on the right bank. The depth-to-fresh rock in the river bed varied from 5 to 12 m. Biotite-gneisses occur along the Balimela penstock alignment, power house site and the tail race channel. The tunnels and the power house are aligned over the hard charnockite and gneissic bands. Deep weathering at the spillway location is under study.

In the earth dam sections, the cut-off trench was taken to a maximum depth of 12 m. in weathered khondalite. A 15 m. deep grout curtain has been provided below the cut-off grade on both the banks.

A major portion of the power tunnel is through massive charnockite, where over break was minimum.

Damodar valley project (*Bihar and West Bengal*)

Four dams-Maithon and Tilaiya across the Barakar river, Konar across the Konar river and Panchet on the Damodar river, have been constructed under this multi-purpose project. The rock types here are granite, granite-gneiss, amphibolite, mica-schist and quartzite with subordinate calc-rock. The regional trend of these rocks varies from N.N.W.—S.S.E. to W.N.W.—E.S.E., with 40° to 70° dip towards E.N.E. to N.N.E.

At the Maithon dam site, mica-granulites and granulite-schist and gneiss trend oblique to the axis of the dam. The rocks are jointed in an irregular manner but become tight at depths. In view of the 12 to 21 m. deep overburden in the river bed, the overflow section is located on the right bank. A shear zone, trending normal to the axis in the spillway foundation was excavated selectively. At the underground power house site located on the left abutment closely jointed granite and dolorite required extensive grouting.

In the foundation area of the Panchet dam, acid granulite, gneiss, hornblende and garnetiferous gneisses and schists are exposed. Mainly sandstone, shale and fire-clays (Gondwanas) are seen at higher elevations on the right bank. The contact between the pre-Cambrian and the Gondwana rocks is faulted. Overburden in the river bed is about 15 m. thick. Hence the concrete spillway has been accommodated on the left bank, across the diversion cut, where fresh and hard rock was met with at 6 to 12 m. depth. At the power-house site, relative settlement along the soft and sheared garnetiferous schist was apprehended, for which shear keys have been provided to transfer the load into adjoining blocks.

The Tilaiya dam rested on alternate bands of quartzite and mica-schist.

Selective weathering resulted in deeper excavation to 341 m. elevation in some schistose bands. The quartzite, though massive, contains intercalations of flaggy material. Weathering along the bedding planes extend from 3.3 to 4.5 m. The soft seams in the quartzite were excavated to a depth equal to their width and back filled.

Folded biotite-gneisses and schists together with hornblende gneiss and schist granitoid in aspect with minor amount of calc rocks from the foundation rocks at Konar dam. The rock exposures trend transversely across the axis and are confined to the river bed where the overflow section was located. The thickness of overburden on the flanks varied from 12 to 23 m. A major shear zone 3 m. in thickness and a few minor shear and fault planes trending oblique to the dam axis are weak features. Selective excavation was carried out in these zones and back filled with concrete.

The poor compressive strength and low values of Young's modulus of the gneisses at the proposed underground power house site downstream of the Konar dam, necessitated the incorporation of a safety factor of 20 to 30 to overcome possible settlement.

Tenughat dam project (Bihar)

A 49.9 m. high rolled earth dam with masonry spillway is under construction across the Damodar river at Tenughat. Gently folded, biotite-hornblende schist, garnetiferous gneiss and amphibolite constitute the foundation. The foliation trend parallel to the flow of the river in a N.E.-S.W. direction with 25° dips towards S.E. Prominent joints trends in N.E.-S.E. (vertical) and N.N.W.-S.S.E. (82° dip towards E.N-E.). Basal joints with low dips, minor shear and fault zones are present in the foundation area.

The low compressive strength, and angle of internal friction of the schists with no cohesion (Table I) have raised the problems of stability in block No. 6. Blocks 5, 6 and 7 have been proposed to be constructed as a single monolith to achieve overall stability.

The model tests interpret that the ski-jump type bucket would scour down to 228.6 m. elevation. A 10 m. deep key trench has been provided at the toe of the dam to control the scour.

Tikerpara dam project (Orissa)

The dam site comprises garnetiferous charnockite and quartz-garnet-felspar-sillimanite-gneiss (khondalite). The foliation strike is W.N.W.-E.S.E., with 65° to 72° dip towards E.N.E. The proposed dam alignment

runs slightly oblique to the foliation. The bedrock configuration, revealed the presence of an old erosional channel. The overflow section is proposed on the left bank since the Khondalite on the right bank is deeply weathered. The non-availability of the fill material in the vicinity of the proposed site influenced the decision for a rock fill dam at this site. Advantage is taken of the competent charnockite and gneisses in locating the spillway, tunnels, and power house.

Teesta project (West Bengal)

The rocks at the site for the high dam across the Teesta river are gneisses interbanded with phyllite and schist. The rocks dip at 40° to 55° on the left and 55° to 70° on the right abutments towards N.N.W. and upstream. Explorations revealed presence of a very deep channel in the middle of the gorge where the depth of overburden is 24.5 m. The minimum standing water depth is 6 m. On the banks, the thickness of overburden is relatively less. Exploratory drifts on the abutments expose well jointed gritty biotite-schist, with gorge material along joint planes. Fine aggregate is scarce at the site.

The major problems at this project would be heavy siltation reducing the reservoir life to only 42 years. The slopes in the reservoir area are quite steep and are prone to slides.

Umiam (Barapani) hydel project (Assam)

In the foundation area of the 72 m. high concrete dam across the Umiam river, quartzite and phyllite (shillong series) are met with. The dam is founded on the synclinal portion of a regional fold. The axis of the syncline trends in N.E.-S.W. The foliation strike is also N.E.-S.W., with 65° to 35° dips towards south-east. The thickness of the quartzite bands vary between 2.5 and 3 m. Phyllite occurs as thin band in these quartzites. A vertical shear zone trending E.N.E.-W.S.W. is encountered on the downstream side of the dam axis. The grey and red phyllite bands, in the central portion of the dam are faulted. Excavation along the shear zones and fault planes have been carried out as per the depth formula. Grouting programme to seal the joints is outlined with holes inclined at 60° to 70° towards north-west in parts of blocks 4, 5 and 7 and towards weat in block 6.

The pressure tunnel is through the gneiss, epidiorite and conglomerate. This zone was successfully grouted. As the dam site lies close to the epicentre of the Assam earthquake of 1897, seismic factor or 0.18 g for horizontal and 0.12 g for vertical acceleration was incorporated in the design.

Rihand dam project (Uttar Pradesh)

At the dam site for the 91 m. high straight gravity concrete dam across the Rihand river, granites, injection gneisses, phyllites and schists, amphibolites and quartzites form the major rock types. The height of the dam was restricted to avoid submergence of Singrauli Coal field.

The jointed nature of the gneissose granite resulting in deep weathering, together with shear zones called for detailed explorations of the foundation by 4,000 m. of drilling. The weathering of the gneissose granite on the right bank extended to 26 m. In the overflow section located in the river bed, it varied from 1 to 6 m. The weathering in the gneissose granites and injection gneisses was capricious, while selective deep weathering was observed in the schistose pockets. Weathered pockets, seams and shear zones were excavated according to depth formula and back filled with concrete. The weathered granite on the right flank indicated compressive strength of 6,000 lbs/sq. inch under saturation. In the reaches where stresses permitted the dam was founded on this weathered rock.

Nagarjunasagar project (Andhra Pradesh)

A 124.7 m. high composite masonry dam across river Krishna with spillway on the river bed and the right and left canals emerging through 1,249 and 2,133 m. long and 8.2 m. diameter tunnels in their head reaches, constitute the main project features.

The dam site is located in a broad 'U'-shaped gorge near the exit of the river in the Nallamala ranges with a broad basin on the upstream. The sedimentaries capping the Archaeans are flat bedded in the hills forming the flanks.

Massive granite gneiss, intruded by dolerite dykes, constitutes the entire river bed. Quartzites and shales of the Srisailam stage (Cuddapahs) unconformably overlie them on the flanks. Over 4,570 m. length of diamond drilling was carried out to determine the fresh rock profile. Attention was bestowed on investigation of the granite-sedimentary contact on the abutments and the intrusive contacts. Weathering in the granite gneisses varied from 6 to 18 m. vertically on the abutments, 0.5 to 4.0 m. in the river bed. Similar weathering extended for 30 and 60 m. on the left and the right abutments respectively. Tests indicated water loss from 10—20 g.p.m. under 30 to 60 p.s.i. and the openness of the joints in the quartzites extending down to the granite contact. The shales and granites were found to be fairly tight.

Three major foundation features required extensive treatment. A 1.5 m. wide shear zone extends from upstream to downstream across block

Nos. 18 to 23 along the contact of dolerite dyke and granite-gneiss in the river bed with considerable seepage. Treatment consisted of provision of a 8.5 m. deep cut-off trench near the heel, excavation of the soft material to twice its width, placement of rails spanning the soft zone and resting on sound shoulder rock, grouting and of facility for drainage.

A fault zone dipping upstream was revealed during excavation below 6 to 30 m. thick fresh granite in blocks 7 to 9 of the left abutment. The thickness of the soft zone associated with this faulting ranged from 0.91 to 4.86 m. consisting of weathered granite, red clay and *moorum*. The soft material was excavated by drifts for 1.5 to 3 m. inside, without disturbing the overlying rock. A ring of plug concrete was placed. Extensive washing and grouting of the fault zone through the overlying rock was also carried out.

Flat bedded quartzites and shales on the abutments, contained thin seams of altered shaly material and clay, which were removed by water under high heads. Some of the buff coloured shales showed a tendency to soften with time. Grouting and electrical analog tests showed negetive results for grouting and deep cut-offs. Excavation nearly 21 m. deep cut-off trenches was in-practicable. Hence a masonry blanket on the upstream extending for 30 m. (100 ft.) sealing of the sedimentaries from direct contact with water, and radial grout curtains extending down into the granite were adopted.

Flat bedded quartzites and shales form the Pasuvemula right canal towards roof falls occurred in this tunnel in the shale portion which are flat bedded quartzites and shales ; Rock beds of the order of 20 m. were anticipated. So permanent supports were provided in a major portion of the tunnel.

Hirakud project (Orissa)

The Hirakud dam is an example of a structure having heterogenous foundations with faulted contacts.

At the site chosen for the 64 m. high dam across Mahanadi, the low relief of the country resulted in the construction of nearly 52 km. long earth dykes on the flanks. The river bed with two wide channels separated by an island, afforded facilities for diversion during construction stage.

Biotite-gneiss, granitoid in aspect and schist on the left bank and the river bed, arkose, quartzite, slate and shale (Cudappahs) on the right bank, form the foundations. The gneisses tend normal to dam with dips 70° to 80° towards the right abutment. The metamorphosed sedimentaries

are synclinally folded. The contact between the gneisses and the sedimentaries is faulted.

The depth of excavation for spillway in the river bed varied from 12 to 17 m. The principal foundation problems on the left bank related to deep selective weathering of the schist bands and the presence of 6 m. thick shear zone trending parallel to the foliation in the left spillway foundation. These were excavated to depths adequate to take the load. The fault zone on the right bank comprised 8 to 45 cm. thick clay gouge and crushed shale. Excavation for a depth 3 m. along the fault zone was carried out. The clay gouge at the bottom of the trench was further deepened to twice its width. A 5.5 m. deep cut-off shaft was provided at the upstream. Besides, a clay blanket upto distance of 90 m. on the upstream was provided over the fault zone. The gneissic foundation rocks on the right banks showed selective weathering along joints and minor faults. Deeper excavation was carried out along a highly jointed zone of epidiorites.

A 4.5 m. deep cut-off trench and a great curtain extending for depths varying from 9 to 15 m. from the bottom of the trench were provided in the earth dam sections. The water loss in the weathered zones ranged from 45 to 90 litres/minute.

Srisailam hydro-electric project (Andhra Pradesh)

The Srisailam hydro-electric project provides a classic instance of problems in sedimentary formations. A 138.6 m. high masonry dam and surface power station are under construction near Srisailam. The main appurtenant works include the construction of foffer dams and diversion tunnels.

At the Patalganga dam site the Krishna river flows through a 275 m. deep V-shaped gorge, having a chord-height ratio of 3 : 1. The 90 m. deep course of the river runs close to the left abutment. The summer water depth 12 m. increasing to over 27 m.

The narrowness of the gorge, the high volume of flood water to be routed, the absence of suitable saddles and the bedded and blocky nature of the sedimentaries at the site influenced the decision for a masonry dam at this site.

Flat bedded quartzite with interbedded shale are exposed in the abutments and in the river bed, excepting the deep course. The deep course of the river has been caused by erosion. Over 3,000 m. of diamond drilling established the sequence of the rock types at depth. 6 to 22 m. thick boulder

fill and a thick sequence of fissile quartzites and sandy shales (Deep channel shales) underlying the massive quartzite in the river bed, with thin seams of clay along the bedding planes. The seismic refraction surveys established the thickness of the boulder fill extending beyond the foundation area. In the deep channel the foundation grade rises from EL 430 at the heel to EL 485.00 at the toe. Studies relating to the permeability, compaction, size and grading of the fill material aided the engineers in the construction of conerete and successful dewatering.

The Quartzites are massive, thick bedded (0.4 to 2 m. thick), blocky, elastic and possess very high strength. The sandy shales of the deep channel possess high strength, elasticity and do not slake. The abutment shales are of low strength, yielding type, and disintegrate on exposure (See Table 1). Water tests indicated losses of the order of 15 tox 20 g.p.m. under 30 p.s.i. in the quartzites.

The chief foundation problems of this site relate to 1) sliding, 2) block jointing and 3) the low strength of the abutment shales.

The low dips of 3° to 7° of the beds containing thin seams of clay and the presence of 27 m. deep pool about 200 m. downstream, create favourable conditions for sliding. The 'C'—value ranged from 80 to 100 p.s.i. and the tan ϕ value was 0.66. Mobilisation of the sliding friction of the side rock by Wedge shaped excavation, provision of a 30 m. wide R.C.C. anchor block at the toe, and construction of the dam a single monolith are some of the measures being adopted. The axis of the dam in this reach was changed to a broad arch and a deep trench at the heel is also considered to minimise the chances of sliding.

The blocky nature of the formation necessitated stage drilling and grouting over the entire foundation area at 3 m. interval.

Mining of the soft abutment shales by drifts and 36 inches diameter holes and placing an impervious balnket on the upstream are being investigated.

A 3 m. thick completely decayed and soft calcareous quartzite was encountered on the right abutment at EL 600.00 associated with a 6 m. wide closely fractured and sheared zone. A 60 m. long drift driven inside the abutment, mined out the soft material. (Chalapathi Rao and Narasimhan and Balasundaram).

Ghata Prabha project (Mysore State)

A 52 m. high masonry gravity dam with catth flanks is proposed across Ghata prabha river near Hidkal. Flat bedded and jointed quart-

zites with minor intercalations of shales are exposed along the alignment overlapped by Deccan Traps on the left plan.

A 13 m. wide and 30 m. deep fault zone is encountered in the proposed spillway reach in the river bed. The material in the fault zone chiefly consists of fragments of highly crushed and broken quartzite, in a clayey matrix. Red clay gouge is present along the foot-wall contact of the fault zone. The fault zone material is heterogenous, highly pervious, settles at the anticipated loads and also not amenable to adequate treatment grouting. Hence an earth fill in the river bed was finally adopted.

Chambal development project (Rajasthan)

Under the programme of development of this valley, the Jawahar Sagar (Kota dam) and the Ranapratap Sagar dams have been constructed.

At the Kota dam site Bhander sandstones with low dips towards downstream are present. The dam, Power House and tunnel are located on the massive bedded quartzitic sandstone with a 20 m. thick sequence of interbedded sandstone and shale on the abutments. Prestressing with cables and concrete plugs to minimise seepage are proposed for the left abutment. Adequate arrangements for free draining of the rock fill supporting the right abutment are provided. Over break and roof collapse in the flaggy sandstone were avoided by depressing the crown of the tail race tunnel.

Kaimur sandstones in the river bed and Rewa shales on the abutments form the foundations at the 58.5 m. high Ranapratap Sagar dam. The nearly horizontal disposition and swelling of shale by about 30% present problems of sliding and settlement. In the sluice blocks, a shear zone containing montmorillonite bearing clay seams are present. Chemical grouting of the clay seam and prestressing of the foundation layers are undertaken. Resistance to sliding is ensured by providing extra concrete loading at the toe of the dam.

At the saddle dam where silty shales form the foundations, bentonite, saw dust, and 'gel' grouting are found necessary for control of seepage. Piezometric holes to observe water levels are also recommended.

Narmada (Navigam) project (Gujrat State)

Detailed geological investigations are under progress for a 140 m. high multipurpose Navagam dam. Three alternative sites, investigated show Deccan traps consisting of massive basalts, amygdaloidal basalts and agglomerates and Bagh beds.

The dam at Navagam dam site No. 1 was found to be very long 1,200m. of masonry and over 3,050 m. of earth sections. Upstream of this site near Mokhadi, the abutment hills are steep where the length of the dam will be about 1,160 m. The Navagam dam site No. 3 has been finally chosen. Detailed geological explorations established the depth to foundation grade to range from 0 to 14 m. the average being 4.5 m. A fault, 15 m. wide runs along the river dipping at an angle of 50° towards 30°W. A 36 inches diameter clay hole revealed the fault breccia to be poorly consolidated. The specific gravity of the material is 2.537 and crushing strength 48 p.s.i. Excavation of the fault zone to a depth of 30 m. and grouting the same are necessary. The adequacy of this treatment needs to be established by model studies based on rock mechanics.

Ukai dam project (*Gujarat*)

A 68 m. high earth-cum-masonry dam across river Tapti is under construction here. The rock types are massive and amygdular basaltic flows intruded by swarm of dolerite dykes. Sand, silt and clay, 20 m. thick covers the left bank.

Three shear zones trending in *en echelon* pattern, run west to east, beneath the alluvium on the right bank. Effective clay-concrete grouting, exemption by deep shafts and provisions of concrete diaphram cut-off are the remedial measures contemplated.

The jointed and sheared nature of the rock in the left transition dam block recessitated shift of the dam axis towards upstream. In the spillway foundations minor shear zones dipping 2 to 5° downstream were thoroughly grouted.

Jointed porphyritic and amygdular basalts at the power house were consolidated by grouting, with the grout curtain extending to 38 m. depth.

Koyna hydro-electric project (*Maharastra*)

This project comprises a 82 m. high dam across Koyna river with an underground power house near Pophli. The dam site, located in Deccan traps comprises massive basalts associated with breccia, amygdaloidal basalts, red bole, and ash. A thin layer of massive basalt underlain by a layer of tuff breccia 10 to 13 m. thick occurs at foundation level. Tests on the breccia indicated high percentage of absorption, erratic variation in modulus of elasticity and compressive strength both in wet and dry condition. Further this rock was also found to be not amenable to grouting. The foundations for the dam in the river bed was taken to a lower basalt layer, involving 18 m. excavation from the original bed level.

A shear zone 2 to 4 m. in width trending N.12°E.—S.12°W. and dipping steeply traverses blocks 12, 13 and 14. This zone continues to a depth of 13 m. with marginal effects of crushing into a lower layer. Weathered and broken material was excavated and back filled with a deeper shaft in the upstream. A gallery has also been provided above the shear zone for future grouting.

The problem of keying the dam in the right abutment through a thick layer of fragmentary rock consisting of red bole, tuff breccia amygdaloidal trap rocks was solved by providing a tunnel into the hill. This was later plugged with concrete and grouted.

With regard to the problems of lining for the pressure shafts where alternative sequences of softer and harder rocks were present, the rocks were classified as good, medium and bad. Good rock was classified as good, medium and bad. Good rock was designed to take 50% of the stresses, the medium rock 25% while the entire stresses were transferred to steel reinforcements in bad rock.

Narmada Sagar project (Madhya Pradesh)

A 88 m. high masonry dam is proposed near Punasa for irrigation and power generation will be led through a system of open canals and three tunnels with a power house on the left bank.

The dam site is located on upper Vindhyan rocks, mostly quartzites interbedded with siltstone dipping at 15°-25° N.N.W. *i.e.* into the right bank. Near vertical shear zones trending E.N.E.—W.S.W. are met with on the flanks, and a fault runs along the left bank. Geological investigations have been recommended along a new alignment selected 300 m. downstream on the basis of relatively less disturbed nature of the rock. The tunnels aggregate 6.3 km. in length, passing through the different variants of traps. As the tunnels may have a relatively small rock cover over them, subsurface exploration to assess the thickness of rock cover and determine geological conditions at the tunnel grade are underway.

Banasagar (Demba) project (Madhya Pradesh)

A 33 m. high masonry dam is proposed across river Son for irrigation and generation of 500 M.W. of power. The dam site is located on the basal quartzite of Semri Series, and juxtaposed against the pre-Cambrian gneisses, the boundary fault marking the contact. A 28 m. deep pool along the river indicates the fault on the basis of surface and subsurface studies. Three more faults have been interpreted on the flanks close to the dam

site. The flanks composed of basal quartzites are relatively thin. Heavy leakage is suspected through them. The reservoir will submerge some of the high grade limestones. The soft shales at the power house site are too soft with low strength. The power tunnel, about 3 km. in length, will pass through rocks of the Kaimur Series comprising quartzites, shales and sandstones.

Conclusions

The foregoing account illustrates the profound influence of geomorphic set-up on the planning, design and excavation of the riverine projects. A thorough appraisal of the geological conditions of the area well in advance ultimately results in great economy both in cost and time.

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ENGINEERING GEOLOGICAL FEATURES OF SOFT ROCK AREAS—SEDIMENTARIES

by

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Introduction

The Palaeozoic, Mesozoic, Tertiary and Quarternary sedimentary deposits mainly covers the soft rock areas in India. The soft rock formations have been preserved in a few valleys in the Peninsular India. They occur extensively in the upper reaches of the Ganga-Brahmaputra valleys, in the Himalayan mountain chains and the Naga-Lushai mountain belt continuing into Arakan Yomas of Burma. Apart from the above locations, these occur in the coastal tracts where they have been laid down in shallow basins during successive periods of marine transgressions and regressions.

The soft rock formations in the Peninsular India have been deposited in shallow fresh-water lakes during Permo-Carboneferous period. These were subjected to the folding, block faulting and epeirogenic movements in Mesozoic and Tertiary times. A continuous stratigraphic succession of soft rocks is exposed in the Himalayan chains, representing an enormous thickness of earlier marine and later lacustrine sediments deposited in the Tethyan geosynclinal sea from Cambrian times. These formations have undergone earth movements of very high intensity during the Tertiary and Quaternary era resulting in complex folds, reverse faults, overthrusts and *nappes* of great dimensions. Some of these movements are still in progress, which are reflected in the form of occasional earthquakes in northern and eastern India. Bordering the Tethyan geosynclinal facies on their southern margin are the Recent and sub-Recent alluvial deposits of Ganga-Brahmaputra plains, with the Peninsular shield south of them (Wadia, 1957).

Bordering the Brahmaputra alluvia on the south and southeast are the Naga-Lushai geosynclinal facies formed of a series of overthrust sheets called the belt of *schuppen* on the N.E. end. Towards the central part of it, lies a major synclinorium consisting of Tertiary deposits ; but towards the south, these have been folded into a series of broad anticlines and synclines with a pronounced N—S axis (Evans, 1958).

Major River Basins of Soft Rock Areas

The major river basins in the soft rock areas are the Indus river system on the northwest, the Ganga-Jamuna system in the north and the Brahmaputra system in the east. The Ravi, Chenab, Beas, Sutlej and Jhelum belong to the Indus basin. The Ganga-Jamuna basin comprise of innumerable tributaries, notable of which are the Bhagirathi, Alakananda, Jamuna, Tons, Sharda, Gandak and Kosi on the northern side and the Chambal and Son rivers on the southern side. The Tista, Raidak, Sankosh, Manas, Kameng, Subansiri, Dibong Siang, Dehing, Dhansiri and Kopili are the major streams forming the Brahmaputra system. The Godavari, Mahanadi and Damodar river system with their merable tributaries drain the soft rock formations in Peninsular India. (Pascoe, 1964; Krishnan, 1949).

Narrow deep defiles still in their stage of youth characterise the valleys in the Himalayan area with thick cover of terrace deposits on the abutments at various elevations. In the peninsular area, the valleys are broad and mature. But all these river systems meander sluggishly in the alluvial plains, before their debouchure into the sea with characteristic swale fillings, point bar deposits, natural levees and backswamps.

Broadly speaking, the outer Himalayas or the lesser Himalayas consisting of the Tertiary and Permo-Carboneferous rocks are characterised by a series of narrow parallel strike ridges, trending East-West in Assam and N.W.-S.E. in Punjab-Kashmir region, separated by longitudinal broad strike valleys with North-South offshoots. On the northwestern corner there is an abrupt change in the direction of strike valleys towards N.E.-S.W. corresponding to the syntaxial bend of the Himalayas. The central Himalayan ridges present a very deep escarpment towards the south and a long gentle slope towards north exhibiting a typical orthoclinal structure. In the inner Himalayas are lofty mountain peaks more than 6000 m. in height rising above a gently dissected plateau country (4000 m. in height) with 3000 m. deep deflies cut up by might rivers. Here many valleys show an abrupt alternation of deep U-shaped gorges and broad shelving valleys of open V-shapes, because of the scantiness of rainfall and corrosion of the area by snow melt.

All the major Himalayan rivers of the Indus, the Ganga-Jamuna and the Brahmaputra systems drain the southern slopes of the Himalayas and northern slopes in the Tibet, the northern watershed extending far beyond the high northern peaks a very clear evidence of the antecedent nature of the Himalayan valleys. For instance, the Brahmaputra flows in a longi-

tudinal valley in a structural trough parallel to the main mountain chain in Tibet with a sharp bend latter, cutting a very deep transverse gorge across the Assam Himalayas. The Sutlej, Gandak, Kosi and Alakananda have also formed deep defiles 1800 to 3600 m. deep. These deep defiles owe their origin mostly to water or glacial action, in some cases, aided by structural features like faults and major joints (Pascoe, 1964).

South of the Brahmaputra in the Naga-Lushai mountain belt, narrow strike valleys feature trending N.N.E.-S.S.W. towards northeast and N-S in the southern margin. Some of these valleys have been carved out along thrust lines and faults fully or partially, as in the case of Manipur, Barak, Doyang, Tirap rivers *etc.* (Evans, 1958).

In Peninsular India, valleys have developed along the margin of Permo-Carboniferous sediments, following lines of old faults and fractures, typical instances being the Mahanadi Valley in Chattisgarh area, the Damodar Valley in Bihar and the Godavari Valley in Andhra (Krishnan, 1949).

Soft rocks—Types and general characteristics

The soft rocks namely the sedimentaries ranging in age from Cambria-to recent can be classified into innumerable types, based on chemical composition, geologic history, mode of deposition, grain size, primary structure, texture and mineralogic composition. However, in relation to engineering geology, they may be classified into two broad classes : soluble rocks and insoluble rocks. The insoluble rocks include rocks composed of essentially insoluble minerals, bonded with generally insoluble cement. Examples of this type are sandstone, siltstone, shale, conglomerate, breccia, indurated clays, mudstone, claystone, coal and other carbonaceous rocks. Soluble rocks include limestone, dolomites, marbles, *caliche*, coquins and evaporites, in which cavernous conditions have occurred or may occur. Soluble and insoluble rocks may be closely associated in an interbedded sequence.

Insoluble rocks can be seperated into rock types, based primarily on their grain size, mineralogical composition, cement and frequency of bedding. The foundation problems in these rocks are dependant entirely on the physical properties of the rocks like compressive and shearing strength, density, absorption permeability etc. Generally the physical strength and intergranular permeability decreases with decrease in grain size and increase in clay content.

Following are the various rock types, with their general characteristics (Trask, 1950) :

Types	Rock Formations	General Features
1. Coarse grained insoluble sedimentary rocks	1. Sandstones, conglomerates and breccia.	1. Hard, durable foundation rocks; brittleness, weak feature, intergranular permeability may less to uplift.
2. Medium grained bedded insoluble sedimentary rocks.	2. Siltstone and coarse slates.	2. Similar to the above, with lower permeability and lower strengths.
3. Fine grained, laminated insoluble sedimentary rocks.	3. Shales - thin bedded and laminer - cemented and compaction types.	3. Plans of bedding generally lines of weekness - compaction type form foundation material - chances of sliding and settlement.
4. Soluble sedimentary rocks.	4. Limestones, evaporites, salt beds, marls.	4. Low strength of earthy types-zones of leaching and solution phenomena chances of leakage.

Properties of soft rocks of various geological ages at different project sites :

Physical properties of rocks like sp. gr., compressive strength, shearing strength, porosity, permeability, absorption etc. are of vital importance in designing the nature of engineering structure and finding the merits and demerits of the project sites. Properties of rocks occurring in different geological ages ta different project areas have been tabulated below and also in Appendix.:—

Eocene sedimentary rocks (Jaintia series) of Kopili Project, Assam

Type of rock	Density gm/cc (lbs/cu. ft)	Absorption %	Void ratio	Porosity %	Crushing strength kg/cm²	Permeability metre/year
Sandstone	2.60 (162.4)	2.00	0.0081	0.81	121.20	31.6
Limestone	2.63 to 2.77 (164.2-172.8)	0.15 to 3.99	0.0011 to .0050	0.109 to 1.190	107.7 to 612.2	—
Shale	2.57 (160.3)	2.85	0.005	0.499	71.3	Impervious

Physical properties of limestones (core specimen) of the reservoir area of Kopili project, Assam

Depth (in metres) of the sample with reference to the type of the limestone formation	Bulk density gm/cc	Absorption (%)	Void ratio	Porosity %	Crushing strength kg/cm²
0.3	2.72	3.54	0.0043	0.429	388.23
6.4	2.76	2.80	0.0038	0.379	479.49
9.4	2.71	1.40	0.0041	0.409	286.68
15.5	2.77	1.30	0.0019	0.189	612.32
21.6	2.72	1.40	0.0045	0.449	410.09
27.4	2.68	1.70	0.0067	0.669	261.68
33.8	2.73	1.20	0.0014	0.139	369.17
41.9	2.74	0.95	0.0046	0.459	414.31
51.1	2.67	—	0.0036	0.359	—
67.3	2.74	0.45	0.0011	0.109	480.4
74.6	2.72	0.15	0.0037	0.369	451.58

Miocene sandstone (Surma series) of Gumti dam site, Tripura

Sample	Sp. Gr.	Absorption %	Crushing strength (dry) kg/cm²	Crushing strength (wet) kg/cm²	Soundness in terms of % loss
1	2.25	9.00	—	—	100 in 3 cycles.
2	2.26	6.98	—	—	-do-
3	2.33	8.40	0.50	0.25	-do-
4	2.26	7.28	0.437	0.125	100 in 2 cycles.
5	2.28	7.29	0.50	0.25	-do-

Upper Gondwana (Triassic) rocks of Tawa project, M. P.

Rock type	Crushing strength kg/cm²	Porosity %	Absorption %	Angle of internal friction	Cohesion Kg/cm²
Sandstone	14.20-562.5	2.6-25.0	2-12		
Shale intercalated with sandstone	—	—	—	15°	0.42

Results of Laboratory tests of sandstone (one samples) from damsite of Tawa irrigation Project, M. P.

Porosity	— 2.60 to 25%
Water absorption	— 2 to 12%
Unconfined crushing strength	— 14.20 to 562.5 kg/cm^2
Unconfined crushing strength of sandstone with some argillaceous beds	— 32 kg/cm^2 and mm
Bearing capacity of foundation rock (from in situ test)	— 63 kg/cm^2 & more
in siuu shear test of shale intercalations	— Phi value 15°, Cohesion 0.42 kg/cm^2

Pliocene sandstone (Lr. Siwalik) at Bhakra dam site, Punjab

Average crushing strength of 56 field samples	Average compressive strength of 6 specimen in dry state	Average compressive strength of another set of 6 samples after soaking in water for 21 days.
3.92 tons per sq.inch (6.17 kg/sq.mm.)	3.87 tons per sq.inch (6.09 kg/sq.mm.)	3.34 tons per sq.inch (5.25 kg/sq.mm.)

Pliocene clay-shale and sandstone (Mid. to Lr. Siwalik) of Ramganga project, U. P.

Type of rock	Plasticity Index	Liquid limit	Plastic limit	Permeability metre/sec	Swelling
Clay-shale	6.0	29.3—22.3	22.3—18.2	2×10^{-10} to 1×10^{-10}	20 to 40%

	Crushing strength lb/sq.in.(kg/cm^2)	Moisture content %	Permeability ft/sec	Modulus of elasticity of sand rock band *p.s.i.* (kg/cm^2)
Sandstone	137 to 307 (9.63 to 21.58)	9.4 to 10.4	0.5×10^{-10} to 1.6×10^{-6} (15.2×10^{-10} to 48.7×10^{-10})	0.42×10^6 to 0.3758×10^6 (2.95×10^4 to $2.63\times10)^4$

Propetties of rocks (Surma Series) of Barak dam site, Assam.

Rock type	Density gm/cm.	Absorption (for 24 hrs) %	Porosity %	Strength Dry kg/cm²	Modulus Elastricity ×104
Fine grained Sandstone & siltstone	1.97	9.3	19.5	170	1.698
Siltstone Essentially	2.03	8.74	17.8	177	0.2857
Siltstone with Shale bands	2.52	—	—	284	—
Sandy shale	2.41	—	—	—	9.848
Shale	2.36	—	—	191	2.48
Shale	2.50	—	—	—	0.1609
Shale with siltstone band	2.38	—	—	94	2.84
do	2.30	—	—	—	0.9613
do	2.44	—	—	98	—
do	2.11	7.4	16.0	176	—
do	2.25	7.8	17.0	90.7	3.937
do	2.14	—	—	—	3.073

Mio-Pliocene (Siwalik) arkosic sandstone at Teesta bridge site, Darjeeling dist.

Compressive-strength dry, tons per sq. inch (kg/sq. mm)	Compressive strength wet (for 72 hrs.) tons/sq. inch (kg/sq. mm)	Dry/wet ration of compressive strength
2.41 (3.78)	1.61 (2.53)	1.50

Plio-Pleistocene sandstone (U. Siwalik) of Beas project

Minimum crushing strength lb/sq. inch (kg/sq. cm.)	Maximum crushing strength lb/sq. inch (kg/sq. cm.)	Average crushing strength lb/sq inch (kg/sq. cm.)
271 (14.05)	1660 (116.71)	3515 (247.12)

General Problems Associated with Soft Rocks

Soluble rocks like limestone, marl etc., develop cavernous and deep sub-surface channels by solution action along bedding planes or fractures like joints and faults. These solution channels and caverns bring the problem of competency of the reservoir. The cavernous limestone in the

reservoir area of Kopili project threatens leakage of the reservoir water and questions the very feasibility of the project.

The conglomerate and breccia when porous and contain high percentage of argillaceous matrix may cause leakage and settlement. Friable and poorly compacted sandstones create the problem of water tightness. Extensive joints or fracturing of sandstone beds caused by folding, faulting or thrusting may also aid leakage.

Some porous sand or silt beds occurring as buried channel or otherwise embedded with compacted rock may produce excessive percolation of water. A thin porous sandy bed embedded with hard conglomerate in parts of the tunnel of Umiam project of Assam created great difficulty in the tunnelling due to rush of the sandy material with water for a period of six months.

Poorly compacted sandstone beds at the toe or abutments cause scouring. When sandstone occurs interbedded with shale, there may be seepage of water through the contact planes. The seepage further lubricates the weak shale surface and aggravates sliding. In steep cuts of abutments, penstocks etc. such slides are frequent when sandstone and shale occur as alternate beds.

The most acute are the problems of the fine grained laminated sedimentary rocks like clayey-siltstone, shales, clay stone, silty-shale etc. as foundation material these rocks have got low compressive strength, and are incapable of bearing the load of heavy structures and give rise to the problems of plastic deformation or shear failure. The shear values of these rocks are further diminished by the presence of joints and weak bedding planes. Smooth surface of the shales and siltstones dipping at low angle to the horizontal accentuate sliding tendencies and the dam may slide along the dip direction. The foundation of the 26 m. high Tigra dam of Gwaliar, M.P. consists of bedded sandstone alternating with shale dipping at low angle toward downstream direction. The dam was filled in 1919 due to uplift and sliding of the foundation rock (Fox, 1935).

The incompetent shale or clay beds when occur with competent members may cause differential settlement. Presence of soft shale bed with hard and compact quartzite in the foundation of the 21 m. high Kedarnala dam at Raigarh, Madhya Pradesh, resulted in differential settlement and failure of the dam in 1964. Creep and slope failures are regular feature in the steep valley walls, road cuts and construction slopes if coustituted of laminated shales and claystone. Some types of clay (*viz* bentonite) and shale cause swelling and slaking under saturated condition and produce settlement by superincumbent pressure and rebound following unloading.

Solutions of these manifold problems associated with the soft rocks requires precise knowledge of the various properties of the rock and designing the structure in accordance with the rock condition. The problems of settlements can be solved by widening the base of the stratum or using spread footing so that the foundation can withstand the load of the structure. Differential settlement is checked by designing articulated structure. Rebound cause buckling of structure and to check it special design is required. Foundation problems of soft rocks with low shear strength can be solved by flattening the embankment slopes or constructing bearms near the toe of the abutments. Under-seepage through pervious strata may be stopped by providing cut-off trench, back filled with impervious material or an impervious upstream blanket and suitable drainage arrangements (Burwell, 1950, Krynine and Judd, 1957).

Engineering Geological Features of Important Indian Projects

Bhakra Nangal project

The main concrete dam is 225.8 m. high, constructed across the Sutlej river near the village Bhakra with a 27·7 m. high concrete dam at Nangal, downstream of Bhakra, with other ancillary structures. The main dam rests on Lower Siwalik sandstone, interbedded with siltstone and claystone, which dip at 55° to 70° towards downstream direction. The sandstone, claystone ratio is of the order of 3 : 1. The sandstones have an average compressive strength of 6.11 kg/sq. mm. (5.88 tons/sq. in) with dry/wet ratio of 1.16, and an average shearing strength of 98.01 kg/sq. cm (1396 lbs/sq. in.)

The main dam is located on one limb of the Ramgarh Dhar anticline. At the entrance of the Bhakra gorge, the lower Siwaliks have been thrust over the Middle Siwaliks with and estimated throw of 1500 m. the thrust contact lying at a depth of 330 m. below the base of the dam. A claystone band known as the Heel claystone occurs at a depth of 150 m. below the dam foundation. Another claystone bed, 76 m. wide is seen downstream from the toe of the dam, and encountered in the spillway, powerhouse and tailrace structures. A third claystone band, 9 m wide is exposed in the middle third section. Faulting has caused duplication as well as elimination of this band at several locations. A short distance downstream of the middle third section, lies a highly sheared siltstone band. In addition, the following weak features are also met with :— (i) Bedding shear zones dipping at 60—70° towards downstream (ii) Diagonal shear zones dipping at 45°—50° downstream and (iii) cross shear zones dipping 15°—30° downstream. (Nickel, Auden, Hazra, Krishnaswamy, Basu, Prasad, Hukku and others, 1945 to 1962).

As remedial treatment for the foundation, the heel claystone was excavated to 46 m. below river bed and backfilled with concrete. A 15 m thick concrete slab connecting the heel to the sandstone member blocks the heel claystone has also been added to act as a strut and transmitting part of the load across the claystone. The bedding shear zones and the claystone—siltstone members were excavated to a depth derived from the formula, 0.002xWxH plus factor of safety (W—width of the weak member, H—height of the dam, safety factor taken as 10 for Bhakra). The excavated portion was backfilled with precooled concrete to ensure stability. The diagonal and cross shear zones had to be strengthened against sliding settlement and leakage. The dam foundations has been further consolidated by cement grouting down to 9 to 15 m. A grout curtain has been provided near the heel of the dam, ranging upto a maximum depth of 90 m. In the left power plant heavy reinforced concrete raft foundation had to be provided, because of the presence of the apron claystone (Nautiyal, Balasundaram and others, 1947 to 1956).

The 27 m. high Nangal dam rests on boulder conglomerates of the Upper Siwaliks. The conglomerates comprises of quartzite, which forms nearly 97% of the bulk composition. The conglomerates are set in sandstone matrix, which have been further hardened in same places by infiltration of carbonate of lime by agency of groundwater. The varying strength of the conglomerate is because of unequal distribution of calcium carbonate of by leacking of the cement, progressively deteriorating on exposure to air. Also lenticles of sand rock gives rise to so called sand pockets.

Beas dam project, Punjab

A 166 m. high and 1700 m. long zoned earth and rockfill dam is being constructed across the Beas river, near the village of Pong. The foundation of the damsite consists of alternating layers of Upper Siwalik sand rock and clayshale, down to 100 m. depth below the base of the dam. The beds dip at 10 to 12° towards N 10°E. The reservoir area is represented by Upper and Middle Siwalik rocks, which have been folded into a syncline (Beas syncline), with the axis trending NW—SE. The dam site is located on the southwestern limb of the syncline. The sandstone and clay-shale beds have been subjected to minor folds, because of thrusting over the alluvial deposit of the Indus valley. Studies by Krishnaswamy, Jalote, Chaturvedi (1959—64) and other have shown periods of movements along the thrust, during Middle Pleistocene, Upper Pleistocene and Recent times. The right abutment of the dam shows two anticlines and one syncline, plunging at an angle of 5 to 40° between N 60° W and N75°W. These three folds have coalesced on the left abutment, resulting in a doubly plunging anticline. This site presents a number of geological problems such

as poor bearing capacity, presence of pervious sandrocks in the cut-off section and transverse fault in the foundation, because of which an earth dam has been designed. The geologically recent satallite thrust and the susceptability of seismic factor of the area to quakes had been taken into account in the design of the structure. The very low dip of the sandstone beds in the intake area of the tunnels may induce slides, which need special type of bolting, to ensure stability of slopes. Geohydrological investigations reveals the presence of artesian conditions in the reservoir area and chances of leakage. In the initial years, the loss is estimated to be about 10% of the total storage, when the reservoir becomes full to the dead storage level. Artesian condition has developed in parts of the dam and reservoir area, because of the synclinal structure in combination with the thrusts.

Ramganga project, Uttar Pradesh

Construction of a 126 m. high earth dam is under progress across the Ramganga river at Kalagarh with a 60 m. high saddle dam across Chunisot towards left bank. The dam site comprises shales, claystones and siltstones, Middle to Lower Siwalik in age. The rocks dip at 50° towards the upstream side. Of the sand rock and clayshales, the clayshales occupy 25% of the area. The sands rock members have low permeability, because of 15 to 20% of clay and silt fractions. The claystone is plastic in nature, the plastic limit varying from 22 to 18. The crushing strength of the poorly cemented sand rock is 137 to 304 p.s.i. The low bearing strength and the poorly cemented nature of the clayshales in the foundation have weighed in favour of construction of an earth dam, in preference to an earlier planned rockfill dam. A number of thrusts are present in the vicinity of the damsite, the nearest located 3 km. downstream of the damsite. In the diversion tunnels (11 m. in dia.) and parts of the intake tunnel, clayshale sequences with dips of 35° presented several difficult situations like slope failure and high overbreak. Provision of berms and easing of the cut slopes, confirmable to the dips have been necessary hence.(Dutta, Nautyal Prasad, Verma, Chaturvedi, Mandhual, 1947 to 1965). The beds strike obliquely to the gorge. Hence the outoff trench, cuts across sandrock and claystone bands. A comparatively higher depth of cutoff has been provided in the sandrock members. In addition, drainage galleries have also been provided for dissipation of any untoward development of pore pressure.

Banihal tunnel project, Jammu and Kashmir

The Banihal Tunnel passes through varied rocktypes such as limestones, slates, agglomeratic slates etc. of Lower Carboneferous to Jurassic and sub recent age. Several thrusts and reverse faults traverse the tunnel

area and the rocks are severely folded (Hazra, Prasad, Srinivasan and Hukku (1953—57). Because of the above geological set-up, immediate supporting, grouting and lining of the tunnel has been carried out with heavy reinforcement in the thrust zones. Because of water movement under pressure in the synclinal area, careful tunnelling was necessary. At the entrance of the tunnel, talus material developed swelling pressures. In general, the engineering geological problems associated with the Banihal tunnel project are water seepage encountered during construction, lining of the tunnel section in relation to rock condition and location of quarries for construction material.

Kishan dam

A 238 m. high arch dam has been under investigation across a narrow gorge on the Tors River for irrigation and power development. Slates, shales, quartzites and Bansa limestone (Mandhali series—Pre Cambrian) are synclinally folded here with a major thrust further downstream on the abutments dipping at 16° towards upstream. The bedding plane dips are low towards the downstream side (Auden, Krishnaswamy & others 1947 to 1968). Exploratory work indicates an overburden of 29.3 m. in the river bed, beneath which the limestones are fresh and hard, but highly jointed. The abutments rocks are also highly jointed, with lack of sufficient rock cover on the left abutment, because of a bend in the river course. Tests conducted gave very low static modulus of elasticity of 0.01×10^6 kg/sq cm. for limestones and 0.008×10^6 kg/sq cm. for the slates, which showed the rock to be inelastic in the abutments and not capable of withstanding high stresses. Hence a rockfill dam has been planned here, instead of an arch gravity dam.

Gumti hydel project, Tripura

A low masonry dam is under construction here, with other ancillary structures. The site consists of fine grained argillaceous sandstone andshales of Upper Surma series. This rock shows a wet crushing strength ranging between 0.25 to 0.125 kg/sq. cm. and dry crushing strength of 0.50—0.43 kg/sq. cm. Poor soundness (soundness value in terms of percent loss is 100 in 2 to 3 cycles) high absorption of 6.9 to 9% and inadequate dry crushing strength does not favour construction of a masonry or rockfill dam. Moreover, there is a dearth of construction material in the area, fit for use or concrete and rockfill dams. Primarily because of the latter consideration a brick core with masonry casing has been designed here (Ray, 1968).

The sandstones and shales here have been folded into a series of N—S trending anticlines and synclines. The damsite is on the eastern limb

of the Jarimura anticline, which in turn is a southern extension of the Atharamura anci-anticline. Because of the thrusting, the rocks are crushed at the axial region. Further soft and loosely cemented rock with high permeability create problems of settlement and seepage. In the power channel alignment, the same sequence of rocks induces slope failure. The powerhouse rests entirely on sandstones. (Ramachandran, 1963).

Farakka Barrage project, West Bengal

The main barrage is located across Ganga on the Gangetic alluvium, consisting of clay, eilt and sand, nearly 35 m. thick. At the upstream lock site, are present different grades of clay and silt to a depth of 14.3 m. from the surface. On the west and east bank of Ganga, seismic surveys have indicated the depth to bedrock (trap) as 150 and 220 m. respectively. Alternate layers of clay and silt are exposed along the feeder canal alignment. Watertable varies between 16 and 24 m. above M.S.L. Though the general slope of groundwater is towards Ganga local troughs and mounds are common. Hence close to the main barrage, water table would rise and cause water logging near the troughs. (Basu, 1962).

Kopili hydel project, Assam

Kopili Project envisages the construction of a 67 m. high dam across the Kopili River and a subsidiary dam of 28 m. high across the Umrong Stream, a tributary to the Kopili River for development of 500 M.W. of electricity (installed capacity). The dam sites will be on Pre-Cambrian gneiss but the bulk portions of the two reservoirs namely the Kopili reservoir and the Umrong reservoir, comprise of Sylhet limestone (Eocene), with numerous sinkholes, cavities and solution channels in it. This Karstic limestone has created the problem of reservoir leakage—a problem, unique in the dam building history of India. (Ramchandran, 1963).

The Sylhet limestone covers 50% of the reservoir spread. The limestone is overlain by Kopili shale and underlain by Cherra sandstone, formations and has a dip of 2° to 5° towards SE. Of the various joint sets in limestone, the two very prominent sets trend NE—SW and NW—SE, dipping vertical. The reservoir limestone is transversed by several faults trending E—W, N—S and NW—SE. Solution along the joint planes and fault zones has given rise to an intricate system of cavern and sub-surface solution channels.

Geomorphic pattern of the project area is such that the lower valleys are towards the dip direction of the rock. The Umrong reservoir is 120 m. lower than the Kopili reservoir and the Langlai valley, situated east of

Umrong reservoir is 190 m. lower than the latter. From surface geological investigation 330 large caverns and sinkholes have been detected. Paleologic study has revealed the presence of several subterranean solution channels some of which are more than 1-km. in length and 20 m. in diametre. Several subsidiary solution channels are connected with the main one and all combinedly has given the appearance of a net-work. Exploratory drill holes have detected cavities of various dimensions at different depths below the cover of overburden and shale. One of these cavity is 43 m. in height and encountered below shale cover of 122 m. Geophysical investigation in the Umrong reservoir area has proved the presence of caverns in limestone at depths varying from 30 m. to 120 m. Geohydrologic study has established that the slope of groundwater level is from the Kopili to Umrong and from Umrong towards the Langlai valley along joints fractures and sink holes. Distinct zones of unsaturated limestone are present at the divides of the two valleys which are the most vulnerable areas to drain out water from the Kopili reservoir to Umrong and Umrong to Langlai Valley under full reservoir conditions.

Tracer study using hodamine dye, potassium dichromate and lime solution could detect several local and short distance interconnections. It has also further proved that through some of the subsurface cavities groundwater is moving at a very high velocity indicative of conduit flow. Investigation by radioactive tracer (tritium) has give evidence in favour of leakages towards this Langlai valley from the Umrong reservoir side. The velocity has been established as 1 cm/sec from various studies. There will be leakage of the order (8.5 m^3/sec) 300 cusecs from the reservoirs. The sectional area of limestone is nearly a million sq m. with solution phenomena assumed forming 1/1000th of this material at the eastern prephery of each reservoir. (Gangopadhyay, 1967).

Barak dam project, Assam

Flood control is contemplated in the Barak Valley, which is essentially a longitudinal valley, aligned parallee to the trend of the Tertiaries. The sites are located in the lower reaches of the valley. Argillaceous rocks of the Surma Series form the right abutment scarp, with low dips of 12° to 30° towards NE into the hill. These are thinly laminated and disintegrated readily on alternative drying and wetting. The river bed and the left bank are entirely covered, forming a flat terrace close to water edge and low mounds further beyond. An overburden of 26 m. in the river bed and 40 m. in the left bank terrace has been provided by exploration. Longitudinal fault has been interpreted to seperate the left bank terrace from the low mounds beyond. A regional thrust fault runs along the Tari bank

further away from the right abutment, with two minor cross faullts in the abutments close to the dam axis. The geological problems here are : 1) The low competency of the fissile shales and siltstones, occurring as foundation material. 2) Thick cover of overburden in the banks and the river bed. 3) Limited space on the right abutment for tunnels for spillway, of adopted. 4 This low strength values of the shales and siltstones under saturated conditions and 5) Non availability of rock fit for coarse aggregate and rockfill.

The problems have been somewhat similar at sites proposed for flood control across tributaries of Barak River, such as Langai, Ruhuni, Sorai and Dhaleswari in Cachar District (Balasundaram & Ramchandram, 1967).

Tenughat dam project, Bihar

The Tenughat Dam Project under construction consists of a 50 m high and 6500m earth dam across the Damodar River at Tenughat, to 0.83 million acre ft (1023 cubic metre). The main purpose of the project is supply of 900 cusecs (25.48 cubic metre/sec) of water to Bokaro Steel Plants and ancillary industries. The 188 m. long masonry spillway of the dam is located on the right bank of the river to discharge a designed flow of 16,000 cubic metre/sec.

The foundation of the dam rests partly on sandstone and shale of the Lower Gondwana and partly on Pre-Cambrian metamorphics. The contact of the Gondwana and the metamorphic is faulted with a 3.6 m. wide zone of gorge and fractured rock. The fault trends parallel to river course with a dip of 50° to 70° towards north. The permeability of the fault zone ranges from 96 to 48 leugeons. To prevent seepage through the fault zone a 20 m. deep cut-off has been provided in addition to 1.5 m. thick upstream clay blanket and 18 m. deep grouting underneath the cut-off.

The reservoir area consists partly of sandstone, siltstone, shale and thin seams of coal of the Lower Gondwana age and partly of the metamorphics. Several faults traverse the Gondwana sedimentaries of the reservoir area. The rocks dip into the reservoir, with predominant bedding and transverse joints. The watertable maps show the interfluve with Bokaro valley acts as a water divide. Hence the geohydrological studies indicated absence of any seepage from reservoir area, as anticipated earlier. (Sen Sarma, 1967, Chowdhury, 1968 & Singh, 1967).

Logtak project, Manipur

This project is the only one of its type in India where drainage of the surplus waters of tectonic lake, named 'Logtak Lake' for reclamation

is to be utilised for power generation. The Project contemplates the construction of a 10 m. high weir across the Manipur River to maintain level of the lake at 770 m. Besides, there will be 4 km. long open channel and 11 km. long tunnel. The open channel will be on recent deposit and the proposed tunnel and weir sites comprise shale, sandstone and siltstone of Disang Series (Eocene) synclinally folded and dipping at an angle of 25° to 50°. The synclinal part comes within the confines of the tunnel alignment. The axis of the syncline trends N—S whereas the tunnel is aligned approximately ENE—WSW The trough of the syncline is occupied by sandstone and the flanks by shale. The power house is located on the flanks of the syncline, where exposed shale with a few siltstone beds are the rocktypes. A thrust fault occurs close to the power house site.

The shale in the tunnel alignment is dark grey and splintery in nature and extensively jointed. Several thin beds of argillaceous sandstone and reddish brown felspathic sandstone alternate with the shale bed. At the intake area of the tunnel about 14 m. of rock cover is available over the tunnel invert. But the rocks are highly weathered, soft and friable. Hence tunnelling in the first 200 m. of tunnel from the intake side will be highly hazardous. In other parts, as the tunnel will pierce through soft and friable shales there will arise problems of excessive overbreak and on rush of groundwater. (Ramchandram, 1966 and Ray, 1968).

Tawa project, Madhya Pradesh

Tawa Project under construction in the Heshangabad district is an Irrigation Project. The main feature of the Project is a 58 m. high earth dam with a central masonry spillway located across the Tawa River, a tributary to the Narmada River.

The dam site is represented by the sedimentary rocks of the Upper Gondwana formation and granite of Archaean age. In the masonry sections, there are current bedded, felspathic and argillaceous sandstones and granites intercalated with the thin lenses (6 cm. wide) of micaceous and carbonaceous shales. In other places, sandstones contain beds of red, purple and olive clayshales. The thickness of the individual bed is one metre or so. All the rocks have southerly dip varying in amount from 10° to 28°.

Laboratory tests have indicated that the rocks have wide variations in their physical properties like porosity, absorption and crushing strength (Table—I). Drill hole data reflects that the softer sandstones are distributed erratically throughout the foundation. Medium to coarse argillaceous sandstone possessing an unconfined crushing strength of more than

32 kg/cm^2 is the predominant rock type. The bearing capacity of the foundation rock determined by *in situ* load test is above 63 kg/cm^2 but the foundation rock has a very low shear strength. Taking these factors into consideration, the base width of the dam has been increased to 56.08 m. so that the maximum applied stress on the foundation is of the order of 8.50 kg/cm^2. To prevent possible sliding, the dam has been designed with light curvature, wider monoliths and entrench in the foundation to a depth of 3 m. below the sound rock level.

Left bank head regulator, gap—IV, Hirakud dam project, Orissa

This is one of the few structures resting entirely on fissile shales, for which region it has been included here. A concrete cum masonry head regulator for supply of water to the left bank main canal, has been constructed within earthen embankments in Gap III. The structure is 63.6 m. long with a base width of 9 m. This reach of the dam consists of fissile Talcher shales (of lower Gondwana age), greenish to greenish brown in colour with occasional boulders of Talcher sandstone, embedded within its shales. The shales trend in E.N.E.—W.S.W. with a very low dip towards S.S.E. or the downstream side. These are covered by a thick mantle of clayey soil, 1.6 to 2.3 m. deep. The shales are brittle, fissile and thinly laminated, breaking into flat pieces parallel to the nearly horizontal bedding planes. The shales deteriorate readily on exposure to air and water. A seepage of 0.1 cusecs was observed at a depth of 4.5 m. below ground bed. *In situ* load tests show a settlement of 0.418″ under a load of 12.41 tons/sq. ft for a period of 66 hrs. No settlement took place after 66 hours. So the shales are capable of supporting the head regulator structure which imposes a load of 2 tons/sq. ft on the foundations. Hence the head regulator was founded at a depth of 8.6 to 6 m. below ground level. The last 0.2 m. surface was excavated just prior to concreting to avoid air slackening of the foundation and covered with asphalt (Acharya, Ramchandran, 1954).

Conclusions

In the above pages, the case histories of various Indian Projects, constructed and under construction, as well as those under active investigation have been briefly discussed, with a view to highlight geotechnical problems that baffle geologists and engineers alike in soft rock terrain. Summing up, the major problems are: 1) The incompetency and low shear values of the soft rocks with possible sliding under saturated conditions. 2) Presence of bedded structures, with shear zones, fault material, intense jointing and fractures, resulting in possible settlement and lateral movement. 3 Thick cover of weathered rock terrace deposits, glacial

fill and slide material, quite often concealing submerged valleys and buried channels. 4) Location of major thrusts in the vicinity associated with extensive sheeted zones with probable movement during earthquakes. 5) Location of the area in a belt of high seismic intensities. 6) Excessive siltation in the valleys in the order of 3 to 5 ac ft/annum affecting the life of the reservoir and 7) The very high flood volumes of the rivers, posing constructional problems like diversion and slippage of abutments by super-saturation during monsoons, with an added threat of extensive slides development in the reservoir area.

The future trend of studies would consist of application of air photo methods for detection of surface and sub-surface structures, development of rock mechanics studies for solution of some of the above problems, methods of consolidation of not very competent rocks, subject to structural disturbances and measures to overcome excessive siltation in reservoirs, besides evolution of consolidation processes to render watertight storage basins, located on pervious material and soluble rocks. Besides, in the coming decades large scale studies may have to be undertaken to study the flood problem in Ganga-Brahmaputra plains and also in Indus, Godavari Mahandi damodar and other origin river basin and devise suitable protection for which the first step would be a geomorphic classification and evaluation of the alluvial basins by geologists.

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References

AUDEN T. B., KRISHNASWAMY, V. S., & MEHTA, P. N. (1947 to 65)—Report on Kishan dam. *Rep. Geol. Surv. Ind.* (Unpublished)

ACHARYA A & RAMACHANDRA, B.(1954).—Engineering Geology of the Herakud dam project, Orissa *Ind. Jour. Power. & Riv. Valley. Dev.* Vol. 10 April '54.

BERWELL E. B. 1950.—Geology in Dam Construction (Berby Volume—Application of Geology to Engineering practice.

BALASUNDARAM M. S. & RAMCHANDRA B., (1965-67).—Report on Barak project, Assam. *Rep Geol. Suv. Ind,* (Unpublished)

BASU S. (1962).—Geological Report on Farakka Barrage project, *Rep. Geol. Suv. Ind.* (Unpublished)

CHOWDHRY A. K., 1968.—Progress Report for the period December to June 1968 Terughat dam project, Hazaribagh dist, Bihar, *Rep. Geol. Suv. Ind* (unpublished).

NAUTYAL S. P., PRASAD V., VERMA R. S., CHATURVEDI A. N., Mandhual and others 1947-65.—Report on Ramganga project, U. P. *Rep. Geol. Suv. Ind.* (Unpublished)

EVANS P., (1958).—Stratigraphy and Tectonics of Assam oil fields.

FOX C. S., (1938).—A comprehensive Treatese in Engineering Geology. *Rep. Geol. Suv. Ind.* (Unpublished)

GANGOPADHYAY S., (1967).—A progress Report on Geological investigation of the Kopili project Assam *Rep. Geol. Surv. Ind.* (Unpublished)

HAZRA P. C., PRASAD K. N., SHRINIVASAN P. B. and HAKKU, B. M. (1953-57).—*Rep. Geol. Surv. Ind.* Reports on Banihal tunnel project. (Unpublished)

JAIN M. S., 1965-68.—Report on Tawa Project, M. P., *Rep. Geol. Surv. Ind.* (Unpublished)

JAIN M. S., (1968).—Reports of Gumti Project. *Rep. Geol. Surv. Ind.* (Unpublished)

Krishnan M. S. (1948).—Geology of India and Burma.

KRISHNASWAMY V. S., JALOTE S. P., CHATURVEDI A. M., (1959-64).—Report on Beas dam project, Punjab. *Rep. Geol. Surv. Ind.* (Unpublished)

KRNYNIE D. P. & JUDD W. R., (1957).—Principles of Engineering Geology & Geotectonics

NICHEL F. A., AUDEN J. B., HAZRA P. C., KRISHNASWAMY V. S., BASU M. C., and PRASAD M. C. V., HUKKU B. M. 1945-1962.—Reports on Bhakra Nangal project, Punjab, *Rep. Geol. Surv. Ind.* (unpublished)

NAUTYAL S. P., BALASUNDARAM M. S., and BAWEZA B. K. (1947-56.—Unpublished G.S.I. Report on Bhakra Nangal project.

PASCOE E. A. 1964.—A manual of the Geology of India & Burma, Volume III, Third Ed.

RAMCHANDRAN B. 1963.—Report on Kopili project, Assam, *Rep. Geol. Surv. Ind.* (Unpublished)

RAMCHANDRAN B. 1963.—Engineering Geology of the Dumbura falls dam sites, Gumti rivers Tripura State, December 1961.

RAMCHANDRAN B. 1966.—A Geological Report on Logtak Lake reclamation cum Leimatak tunnel Manipur, *Rep. Geol. Surv. Ind.* (Unpublished)

RAJ S. 1968.—A Geological Report on Logtall Hydroelectric and Reclamation project, Manipur, *Rep. Geol. Surv. Ind.* (Unpublished)

SEN SARMA S. B. (1967).—Geological Report on the Tenughat Project, Hazaribagh district, Bihar, *Rep. Geol. Surv. Ind.* (Unpublished)

SINGH V. P. (1967).—The Geotechnical note on the Teunghat dam project, Hazaribagh district, Bihar, *Rep. Geol. Surv. Ind.* (Unpublished)

TRASK, P. D. (1950).—Applied Sedimentation.

VERMA R. V. & CHATURVEDI S. N. (1968).—Physical and Engineering properties of Siwalik rock as foundation and tunnuling media—an evaluation of field & laboratory Test data.

WADIA D. N. (1957).—Geology of India.

GEOLOGIC CAUSES FOR MISHAPS AND FAILURES OF ENGINEERING STRUCTURES

by

P. N. MEHTA, M. SC. AND S. R. PRADHAN, M. SC.

Introduction

Almost every week, technical journals all over the world report on failure of at least one engineering structure. Some of them have failed inspite of seemingly adequate investigations, design and construction. Three attributes are essential for the successful execution of engineering projects, namely, knowledge of precedents, thorough aquaintance with the advances in soil and rock mechanics and a good knowledge of geology. Here the last mentioned attribute, namely geology, is discussed with reference to its role in mishaps and failures in engineering structures. Apart from discussing the geological causes for the failure of some of the engineering projects already constructed, the geological causes of the tunnel collapses during construction, and damages to the engineering structures caused by landslips have also been discussed.

Failure of Dams

Analyses of the causes of the failures of the dam structures all over the world point out that about 40 per cent of the failures could be attributed to the adverse foundation conditions at the sites. Rao (1960) has listed the failure of the Indian dams and weirs. Out of these, a few of the failures are due to the geologic causes. After 1960, a few more dams were breached; the causes of which could be related to their weak foundation conditions.

Failure of earth dams

The failure of earth dams may be due to the following geological causes :—

i) Development of high pore pressure
ii) Piping and sloughing of the foundations
iii) Saturation of the foundations

Failure due to excessive pore pressure

In India, failure of the earth dams due to excessive pore pressure has not been reported. An instructive example of this type of failure is offered

by the failure of the Fort Peck dam in Montana, U. S. A. It is an earthfill structure, 78 m. high and resting on 50 m. thick strata of sandstone and shale and it failed during construction. The upstream portion of the dam slipped due to excessive pore pressure developed in the foundations of the dam. During the reconstruction of the dam, slopes were flattened and relief wells were provided on the downstream side, which proved to be effective (Legget, 1962).

Failure due to piping

Dudhawa dam, Madhya Pradesh : The 3.2 km. long and 24.4 m. high Dudhawa dam was completed before the rains of 1962 with scheduled filling in the same monsoons. During filling, area on the downstream side became water logged and slushy and at a few points the water was bubbling out of the dam. After thee years of operation, the seepage increased. So the reservoir was emptied and remedial measures such as the upstream clay blanket and the relief wells on the downstream side were provided (Sinha, 1968).

Construction records show that in the river portion, the cut-off trench rests on weathered granite. Across the old channel of the river, also a positive cut-off was provided to bed-rock. The rest of the dam is located on a 1.8—6 m. thick clay bed, where only a puddle trench was provided. However, there was a thick section of sand below the clay bed, which had not been excavated during the construction. This accorded avenues of seepage after the construction. Further, a few quarries had been opened up on the upstream side, which too exposed the sand-layers probably extending downstream, facilitating downstream movement of stored water.

Kedarnala dam, Raigarh district, Madhya Pradesh : Kedarnala dam, 21.3 m. high earth dam, was constructed in 1964 on quartzitic sandstone intercalated with shale. On the 4th July, 1964, there was a rainfall of 408 cm. in 13 hours. On the 6th July, muddy water started coming out near the junction of the rear boulder too and the ground. Very soon water was coming out from the embankment slope above the boulder toe and the piping action continued further, with breaching of the dam in a few hours.

A study of the probable causes of the failure indicates that differential settlement in the earth work created a passage for water resulting in dam collapse. Another possibility was the existence of a chance blind drain fillled with silt and sand in the foundation which remained untreated during construction and formed potential avenues for water, responsible for the piping action leading to eventual breach. Differential settlement and sudden filling due to heavy and concentrated rain could have been the contributory factors.

The post-failure geological inspection of the site indicated that the failure might have occurred due to unequal compaction of the earth section of the dam.

Failure due to saturation of the foundation and settlement

Ashti dam, Maharashtra : This 18 m. high earth dam constructed during the years 1876-83 failed in 1883 and again in 1923. The failure of the dam has been attributed to the lack of proper drainage facilities which resulted in the saturation of the foundation material. Cousequently, there was settlement of the structure which also slipped in the downstream direction (Rao, 1960).

Seepage from the right bank of Hirakud dam, Orissa : The 15.2 m. high right dyke area is underlain by the granites, weathered to depths of over 6 m. depth. The cut-off trench below the dyke has been mostly taken into the residual soil such as clayey, weathered rock and sandy weathered rock.

On 20th October, 1957, a small pool was noticed at R. D. 24,550 ft., downstream of the service road at a distance 36.5 m. from the toe of the dam. Water was coming out with fine cream coloured clayey particles. These boils gradually developed over an area 12 sq. m. in patches. The water table also was very high in this area, since it was bound by reservoir on the upstream side and main canal and its tributaries on the downstream side.

On 12th November, 1957, when the reservoir was at R. L. 628.80 ft. several boils were noticed between R. D. 23,400 ft. and R. D. 23,450 ft. at a distance of 122 to 183 m. from the toe in a valley at four places. The top crust cracked and the boils appeared at the surface. The boils were because of seepage from the reservoir through the sub-surface of residual soils under the cut-off trench. As remedial measure, an impervious blanket has been provided on the upstream side with relief wells on the downstream. Further loading with rock-fill has been made to counteract uplift pressure on the downstream and avoid formation of boils. The seepage has considerably decreased after construction of the upstream blanket (Jena, 1966).

Seepage from Kangsabati Reservoir, Bankura district, West Bengal :

The lower Kangsabati reservoir with a capacity of 130 sq. km. is being formed with a 10 km. long and 41 m. high dam with a 140 m. long left side saddle spillway, upstream of the confluence of Kangsabati and Kumari rivers. The seepage of water from the Kangsabati reservoir has been noticed through the foliation trend of the rock formations on the left abutment.

Soft, weathered, jointed and sheared sericite phyllites and greenish chlorite phyllites with thin quartzo-felspathic impregnations form the rock types in the area. At the time of final foundation stripping, water started seeping from Ch.7 towards Ch. 10, with minor amount of seepage at Ch.6. A positive cut-off in the heel portion of the dam, a clay blanket on the upstream side extending upto Kangsabati abutments and grouting the foundations area by means of shallow inclined vertical holes have been recommended (Hazra, Ramachandran and Basu-Engineering Geology Division files).

B. Failure of Masonry and Concrete Dams

The failure of masonry or concrete dams may be due to the following geological factors :—

i) Development of tension due to excessive uplift pressures and sliding of the dam on its foundations or on a horizontal section. This may occur after some years during which the foundations may get soaked and lose friction.

ii) Crushing, piping, softening, eroding or undercutting of the foundation material and

iii) Spilling over to excessive height causing tension and scour.

Review of the failures of masonry and concrete dams in other countries

A few recent cases of the failures abroad are discussed in the following paragraphs :

Malpasset dam (*France*) : The 61 m. high arch dam constructed in 1954 collapsed suddenly after seven days of unusually heavy rain, resulting in a catastrophic flood taking toll of 344 lives. The failure of the dam has been attributed to the rupture of the foundation rocks comprising mica-schist reported to be sheared and jointed, with a wedge shaped mass overlying a clay-filled seam (Krynine & Judd., 1957).

Baldwin dam (*California*, U. S. A.) : On Saturday, December 14, 1963, the Baldwin hills reservoir was destroyed by the failure of its foundation. The area is underlain by sedimentary formations—sands, silts and gravel, partly loose and partly consolidated, overlying schist. Several minor faults were mapped in the vicinity of the reservoir during construction. The breach developed along the plane of fault though the movement was apparently not seismic. Progressively increasing displacement resulted in rupture of the reservoir lining and consequent entry of water under pressure into faulted foundations. Erosion of the foundation proceded rapidly, causing uncontrolled leakage which led to total failure (Jansen *et. al.* 1967).

Vaiont Reservoir (Italy) : The worst dam disaster in history of dam construction occurred on October 9, 1963 at Vaiont dam, when almost 3,000 lives were lost. This highest thin arch dam 266 m. tall sustained no damage in the main shell or abutments. This catastrophe occurred because of slides, was caused bv the combination of adverse geologic features in the reservoir area.

Failure of masonry and concrete dams in India

There are three recorded failures of masonry dams in India in the pre-Independence period. These are i) the 31 m. high Pagua dam which failed in 1923 due to the overtopping the dam, ii) the 45 m. high Kundli dam which was destroyed in 1924 due to the occurrence of floods before the masonry had time to set and iii) the 28 m. high Tigra dam which failed in 1919 due to uplift and sliding on the foundations. Of these the first two failures can be attributed to the engineering causes whereas the failure of Tigra dam is purely due to defective foundation conditions which were not suitably remedied (Fox, 1935). More recently the Kalisind weir in Rajasthan breached in 1956 and 1960, which can partly be attributed to geologic causes.

Tigra dam, Madhya Pradesh : This gravity dam was about 1.6 km. long and 25.8 m. high and arched to a radius of 35,052 m. The structure was constucted of very strong sandstone masonry. The breach was 396 m. across. The dam broke into several large blocks measuring 30 m. to 61 m. in length and were bodily pushed forward. The structure rested on bedded and joined sandstone with thin layers of shale, dipping at low angles towards downstream, a condition most favourable for the sliding, unless the dam is suitably anchered. The foundations were not taken more than 38 cm. to 61 cm. into the exposed bed-rock. Conseqently, on the very first occasion when the full reservoir pressure was built up, it was destroyed. The percolation of the water into the foundation rocks through the joints, exerted an uplift pressure which aided in the sliding of the dam on its foundations (Fox, 1935).

Kalisind weir, Rajasthan : This 6 m. high weir, across Kalisind river constructed in April, 1956, during the floods of July, 1956, was washed away in parts. The cause of this failure was presumed to be the poor setting of the mortar in the masonry structure. The second failure took place during the high floods of August, 1960 when 2.4 m. deep flood waters overtopped the structure. Blocks of masonry were bodily moved about 30 m. downstream. In certain portions of the breached section of the weir, the rock was found to be appatrently intact, with few cm. to a few metres of masonry sticking to it while in other portions the masonry have been stripped clean off the foundations.

The foundation rocks at the site consist of well-cemented, thickly bedded sandstone, showing a dip of 3°-6° towards upstream; and several sets of joints, which at the surface were either incipient or open.

The failure of this weir within masonry appears to be due to the poor mortar bond. Where the failure had taken place at the contact of the foundation rock and masonry, ineffective bond appears to have resulted in a lowering of the shearing friction factor at the contact and consequent failure of the superstructure by shear and sliding (Chaturbedi, 1961). It has been recommended that during reconstruction the foundation should be taken 0.9-1.2 m. below the river bed at the toe and stripping the foundation in an upstream direction so as to provide a sufficient wedge of concrete to counteract sliding tendencies.

Dhandraul dam, Mirzapur district. Uttar Pradesh : The 20 m. high dam on Ghaghar Nadi is located on the massive and compact vindhyan quartzites. These quartzites are intersected by closely spaced and open joints often upto 8 to 10 cm. in wdith which are fairly continuous. The Dhandraul dam was completed in the year 1917. Leakage of water from its foundation started after a trouble free performance of 9 years. The initial discharge of 0.15 cumces (5-6 causces) in 1926 increased to 0.85 comecs (30 cusecs) by 1936 and continues still (Srivastava, 1961).

Mishaps in Tunnels

Roof collapse and the consequent blocking of the tunnels are commen features in highly folded and structurally disturbed heterogenous rocks in the Extra-peninsular regions than in the Peninsular India.

The tunnels in the Himalayas are generally located at great depths from the surface. Thus, inspite of detailed surface investigations coupled with limited sub-surface studies by means of drilling vertical holes from the top and horizontal holes from the tunnels as the excavation proceeds, difficulties have arisen leading to roof collapse and holding up construction schedules.

Tunnel collapse may be due to one or a combination of the following factors :

1) Insufficient rock cover over the crown of the tunnel
2) Highly jointed and sheared nature of the rock
3) Inflow of groundwater
4) Swelling clays

In all these contingencies careful blasting, special tunnelling techniques and proper and timely roof supports are called for in order to ward off troubles. The mishaps in some of the tunnels are discussed here under :

Umiam hydel project, Assam: This project envisaged the construction of a dam 2134 m. long 3 m. diameter tunnel and 580 m. long penstocks and a power house. All the structures were completed by 1964 except the tunnel which was held up due to sudden flow of silt and sand that chocked the outlet portal and a chimny was formed effecting a length of 60 m. (Gangopadhyay, 1967). The tunnel pierces through quartzites, phyllites and metamorphosed conglomerate of the Shillong series (pre-Cambrian) and the metadolerite. Where the roof of the tunnel has collapsed, metadolerites are exposed. Insufficient rock cover above the tunnel grade, high degree of weathering and intense jointing of the rock were mainly responsible for the formation of the chimney. An open out in this portion with R. C. C. lining was decided. However, for two successive years, there were huge landslides from the cut walls due to the steep slopes of the cut wall, advarse disposition and openness of the joints and excessive percolation of water. By speeding up the excavation of the open cut and limiting the construction work to the dry period, hazards of failure were averted and tunnel was completed.

Trouble also arose in this tunnel at Face 4 where there was sudden rush of silt and loose sand from the moderately compacted sandstone bed in the pervious conglomerate. The entire tunnel face was chocked by the silty material, with suspension of work for six months.

Jaldhaka hydel tunnel, West Bengal : A barrage across the Jaldhaka river diverts 7 m^3/sec. (250 cusecs) of water, through a 4 km. long water conductor system, into 168 m. deep surge-cum-drop shaft. The pressure tunnel at the bottom of the shaft leads the water into penstocks.

Tunnelling through the highly folded and sheared schists, quartzites and gneisses presented innumerable difficulties. Failures from crown and walls were frequent retarding the progress of work. The E. W. pressure tunnel is parallel to the strike of the foliation of quartz-biotite schist. The overbreak was confined to the Northern wall and neighbouring crown portion. Maximum overbreak was 23.8%. A chimney, 19 m. high above the spring level, was formed due to collapse after the excavation.

The main headrace tunnel, aligned in N-S direction follows the dip direction and passes through soft schist, quartzite and gneisses. Overbreak in gneisses and quartzite was confined to shear zones and jointed areas. Loose blocks of the maximum size of 1.22 x 0.91 x 0.30 m. of rock fell in the tunnel faces 8,7 and 2. The schists rapidly detereorated after

excavation and showed distinct trend of disintegration with the passage of time. The rocks in contact with moisture in the tunnel started peeling off from the crown.

The causes of the failures in the tunnels have been attributed to 1) schistosity and bedding cleavage 2) joints 3) shear planes 4) water seepage and 5) the blasting pattern adopted (Choudhury, 1966).

Power Tunnel, Ramganga dam project., Uttar Pradesh : The crown of the 10.97 m. diamter power tunnel collapsed during construction near its downstream portal. The outlet portal is situated at the bottom contact of clay-shale-siltstone band with sand-rock (Middle Siwaliks). The cover of rock on the crown was about 32 m. which was just twice the diameter of the tunnel. The tunnel was excavated through a sequence of clay shale, blocky to jointed, silty sand-rock, and a sheared 12 m. thick clay shale band with streaks of sand-rock (Prasad and Dutt, 1965).

The first collapse of the tunnel took place on the 25th January, 1964, followed by another on the 2nd February, 1964. The sheared clay shale 12 m. wide, was considered to be the main cause of the rock-failure on the crown of the tunnel. Measures to hold the tunnel in position, before its failure, consisted of putting up, through the excavated section, steel ribs at 1.5 m. centres and timber logging of the crown wherever extra excavation had been done.

These precautions did not prove adequate. The steel supports were observed to give way under the load of the rock on the crown which was apparently getting displaced. Ultimately a major collapse of the crown rock at and beyond the portal took place on 13th May, 1964, with the formation of a chimney in the crown. The collapse had taken place in the first 33m. lenght of the tunnel in which portion all the steel ribs and timber had been razed to the ground. A programme of holding the rock face at the edge of the collapse by driving perfobolts and providing a concrete arch portal were executed. (*op. cit.*)

Damage Caused to Engineering Structures by Landslides

The surface power houses and the penstock structure in the Himalayas are likely to be seriously damaged by the failure of hill slopes behind the structures. Therefore, the stability of the slopes adjoining these structures need critical study, to decide the feasibility of the project. Thus the entire layout of the Yamuna Hydel Scheme, Stage II in U. P. had to be changed since the slopes behind the proposed location of the power house at 6.4 km. (mile 4) of the Kalsi-Ichari road, was steep and prone to rockfalls

and-rock-slides. Some of the more glaring examples of the damage due to this geological factor are summed up below :

Leimakong Power and water-supply scheme, Manipur : The total damage to the weir, water conductor system, bridges and the power house at Leimkong has been attributed to the huge landslide debris which blocked the streams initially and later on breached causing floods and damage (Balasundaram and Ramachandran, 1967). The Scheme is located in the hill ranges made up of shales and sandy shales with subordinate amount of sandstone (Disang), dipping 35°to 75° towards W.N.W direction. The rocks are folded and crushed with a thick weathered mantle consisting of hillwash and talus with clay and silt. These conditions rendered the hill slopes potentially unstable. In 1962, after a period of heavy rainfall, the steeper slopes were saturated and became mobile. The greater gravitational pull and loss in shear resistance led to greater instability and caused the slides and floods, which damaged the structures. The project has since been reconstructed.

Pallivasal Hydro-electric project, Kerala : Another accident due to landslides occurred at the Pallivasal Project, where the alignment of the penstocks was displaced. The landslides occurred between anchor block No. 1 and 4 (Ali and Balchandran, 1967).

The slopes over which the penstocks have been laid consist of pre-Cambrian rocks with soil cover and rolled boulders ranging in depth from 1.80 m. at the valve house to 40 m. between anchor block No. 1 and 3. These seem to be a part of an old landslide. The ground slope along the penstock even normally appears to have been critical and unstable. The slope failed due to heavy continuous rainfall, saturation of the material and poor drainage.

Neriamanglam Power House, Kerala : The slide near the surge shaft of the Neriamanglam Power house, on 3rd July, 1967, released about 850 cubicmetres of soil and debris and flow of 14 m^3/sec. (500 cusecs) of water which filled up the power house under erection. Balasundaram (1967) considers that the slide was confined to the soil and highly weathered loose debris above the bedrock. This appears to have been caused by over saturation of the slope material by heavy rainfall.

Landslide at the right abutment, Jaldhaka hydel project, West Bengal : The right abutment slope of the barrage was effected by a landslide during 1964 monsoon. The slide material choked the intake structure of the weir located at the toe of the hill. The rock types in the affected area consisted of weathered, blocky gneiss. The overburden matarial slopped

and exposed the *in situ* rock. Thirty to Sixty metres wide cracks trending in N-Sand E-W directions developed on the top of the slip zone indicating further possibility of the slide. It appears that the slide was due to incompetent geological formations, their advance disposition, physical character of the rock, effect of water seepage and the blasting done at the toe of the slope (Choudhury, 1966).

Landslips in Noozhiyar Power House area, Sabarigiri Hydro-electric project, Quilon district, Kerala : Charnockitic gneiss forms the main rock types in the area. The hill slope between the tail race and switch yard was covered with soil and boulder down to 24.3 m. depth. Landslips occurred in the areas adjoining the tail race and switch gear yard in June, 1963, after heavy rains. Rao (1960) attributed the causes of the formation of the slide to increase in pore pressure in the soil because of heavy rains, toe cuts in the tail race excavation and blasting in the nearly tunnels.

Damages to Engineering Structures due to Earthquakes

The damage due to earthquakes are too well known to be emphasised upon. At every project, whether located in the well establised earthquake belt of the Himalayas or in the relatively more stable land mass of the Peninsular India, seismic studies have to be undertaken and a proper seismic factor is to be provided for in the design of the structures. A recent example of earthquake damage need only be mentioned here to impress upon the need for such studies. The Koyna dam 96.6 m. high of rubble concrete was rocked on the 11th December, 1967, by an earthquake. The dam was subjected to an acceleration of 0.42 *g* (horizontal) 0.39 *g* (along the axis of dam) and 0.34 *g* (vertical), compared to the 0.05 *g* provided in the design. But the dam escaped failure.

The main dam, composed of 40 monoliths of width 15.24 m. is seperated by construction joints. These monoliths have been subjected to severe movement as is noticed from the foundation and operation galleries. In the monoliths in river bed, the plaster at the junction of the monoliths has been peeled off and these have increased the seepage from the gallery portions. The heaving in monolith 26/27 and 27/28 is attributed to the presence of a buckled up section of the lower basalt layer, immediately below the foundation grade. Another probable cause of this displacement may be the steep (10 m.) difference between the foundation levels of monolith 26 and 27 (Report on Koyna earthquake by Officers of G.S.I, 1968).

The spillway bridge and road above the dam have been affected by this shock. The junction on the left side retaining wall and spray wall shows a slight shift of 8 mm. (1/4″) towards east.

Cracks in the three bus bar passages were noticed at a distance of 1m. from machine hall of the underground power house. In the arch of the Transformer hall cracks were present near units 2, 3 and 4. Near the Surge and river gallery sections ground creaks were present in the approach road and about 200 m. away from the river.

The century-old Helwak bridge over river Koyna on Guhaghar road has been destroyed consequent to the collapse of the three central spans of arch masonry, and two piers during this earthquake.

Concluding Remarks

The experience gained by the study of above enumerated failures and mishaps proves beyond doubt that a structure is only as strong as the weakest foundation member. A structure is designed to meet the requirements necessary for the safety of the structure, keeping in view inherent deficiencies of the formations at the site. The work is a success as long as the foundations remain intact and behave as one unit. But sometimes powerful and uncontrolable forces try to disrupt this harmony and consequently destroy the structures.

The following precautionary measures would help to avoid catastrophes caused by the destruction of engineering structures :—

1. Through pre-construction investigation and proper evaluation of data including geological factors are essential. Design must be adopted to suit the geological site conditions.
2. Designer must evaluate all the possibilities of deformation at the site, including subsidences and the slips caused by human agencies, natural tectonic movements and heavy precipitation.
3. Unexpected conditions uncovered during construction should be carefully assessed and the structures redesigned if necessary.
4. Construction problems must be analysed carefully to detect possibility of major failures by experience gained from local troubles.
5. Formation of dam safety division, comprising engineers and geologists to look after constructed structures:

References

ALI HAMZAH and BALACHANDRAN V., 1967.—Landslides along the penstock alignment Pallivasal Hydro-Electric Project, Kerala, *Jour of Eng. Geol*, Vol. II, No. .1.

BALASUNDRAM, M. S., 1967.—Soil slide near the surge shaft of Nariamangalam Power House, Kerala State, *Jour. of Eng. Geol.* Vol. II, No. 1.

BALASUNDRAM, M. S. and RAMACHANDRAN, B., 1967.—Geotechnical Aspects of Landslidos in Leimakong Power and Imphal Water Supply Schemes, Manipur State, *Jour. of Eng. Geol.*, Vol. II, No. 1.

CHATURBEDI, S. N., 1961.—A note on the breached weir on the Kalisind river, Jhalawar district, Rajasthan, *Rep. Geol. Surv. Ind.* (unpublished).

CHOUDHURY, A. K., 1963.—Progress report for the period November, 1962 to July, 1963 on Jaldhaka Hydro-electric Project, Stage I, Darjeeling district, West Bengal. *Rep. Geol. Surv. Ind.* (unpublished)

CHOUDHURY, A. K., 1966.—Progress report for the period January, 1965 to July, 1965 and November, 1965 to July, 1966 on the Jaldhaka Hydro-electric Project, Stage I, Darjeeling district, West Bengal. *Rep. Geol. Surv. Ind.* (unpublished).

FOX, C. S., 1935.—A comprehensive Treatise on Engineering Geology. The Technical Press Ltd., London.

GANGOPADHYAY, S., 1967.—Mechanism of rock-slide in parts of tunnel of Umiam Hydel Project Stage I, Assam. *Jour. of Engg. Geol.* Vol. II, No. 1.

JANSEN, ROBERT, B, *et. al.*, 1967.—*Proc. of Am. Soc. of Civil Engg.* Vol. 93, Nos. SM4.

JENA, A. B., 1966.—*Jour. of Soil Mech. and Found. Engg.* Vol. 5, No. 3.

KIERSH, GEORGE A., 1964.—*Trans. Am. Soc. Civil. Engrs.*, March 1964.

KRYNINE, D. P. and JUDD, W. R., 1957.—Principles of Engineering Geology and Geotechniques, McGraw Hill, Kogakusha.

LEGGET, R. F., 1962.—Geology and Engineering, McGraw Hills, Kogakusha.

OFFICERS of G. S. I., 1968.—A Geological report on the Koyna Earthquake of 11th December, 1967. Satara district, Meharashtra State. *Geol. Surv. Ind.* (unpublished).

PRASAD, V and DUTTA, A. K., 1965.—Progress report No. 1 on the construction stage geological investigations for the Ramganga river Project, District Garhwal, U. P. during the period October, 1963 to September, 1964. *Rep. Geol. Surv. Ind.* (unpublished).

RAO, K. L., 1960.——Failure in Dams and Weirs, *Bhagirath*, July.

SINHA, D. S., 1968.—Dams in Distress, *Jour. of Central Board of Irrigation and Power*, Vol. 25, No. 3.

SRIVASTAVA, K. N., 1961.—Report on the Geological Investigations of the leakage problem at Dhandraul reservoir, Mirzapur district. *Rep. Geol. Surv. Ind.* (unpublished).

CONSTRUCTION MATERIAL AVAILABLE IN INDIA AND THEIR UTILISATION IN ENGINEERING PROJECTS

by

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Introduction

Availability of proper construction material has a vital bearing on the economic implementation of any major civil engineering project. Examples are not rare, where a project, otherwise feasible, has been dropped for want of suitable construction material. Alternatively the type and the design of a structure have been drastically modified to suit locally available construction material. For example, at Sharavathy project, sand was not available and long distance haulage of cement was costly. Hence stone masonry-in-lime *surkhi* morter was adopted for construction, thereby saving millions of rupees to the project. Similarly the dam for the Koyna project was constructed of rubble concrete and the Mundli weir in Orissa and the Dak Pathar barrage in U.P. were constructed of colcrete instead of concrete.

Naturally occurring materials such as rock, sand, silt and clays usually form the construction materials. Of these, rocks are the most largely used construction material such as coarse aggregate, rock-fill, masonry blocks and rip-rap. These have been in use since the earliest days of civilisation. However, with modern practice of dam engineering and the advances made in the science of soil mechanics, other natural occurring fine materials like sand, silt, and clays have found full use in the construction of earth and rock-fill dams.

Two important aspects to be considered in the selection of proper construction material are (i) it should be easily available in the required quantities in the vicinity of the project site and (ii) it should be suitable for the type of the structure envisaged. All types of rocks available on the earth's surface are not suitable for engineering construction. Hence the rocks to be used for construction have to be tested. These tests include the determination of the confined compressive strength, shear strength, tensile strength, modulous of elasticity, chemical reactivity, consolidation,

permeability, natural and dry density, moisture content, slaking, and shear characteristics etc.

Suitability of Aggregate for Concrete

The mineralogical, physical and chemical properties of rocks including the suitability as aggregate originate from geological conditions and the process of weathering to which they are subjected. Understanding of the intrinsic properties of the rock is required for the most effective selection of an aggregate. Petrographical and mineralogical studies are necessary to understand these properties. Thus a geologist becomes the most important judge for the selection of the most suitable type of construction material.

Specifications have been laid down by the Indian Standards Institution for the rocks to be used as concrete aggregate. These specifications are based on empirical tests. Scope for deviation from these specifications is possible and a geologist's service can be most effectively utilised when such deviation become necessary. According to the Indian Standard Specification, any rock proposed to be used as concrete aggregate should be dense with specific gravity of 2.6 as minimum. The deleterious material such as coal, clay lumps and soft shales etc. should not exceed 5% by weight of the total aggregate. The rock should be sound and there should not be loss of more than 12—15% in five cycles of sodium sulphate soundness tests. The loss due to abrasion in Los Angles rattler test should not exceed 10% in 100 revolutions and 40% in 500 revolutions. Water absorption of the rock should be less than 5% but preferably it should be restricted within 1%. The compressive strength of the rock to be used as concrete aggregate normally exceeds more than 25,000 p.s.i. (1760 kg./sq. cm.). However, there have been instances when the concrete made of aggregates satisfying all these specifications are not of required strength while some concrete made from slightly poorer aggregate possess required strength and were successfully used.

Distribution of Rocks Used as Concrete Aggregate and Masonry Blocks

More commonly used natural concrete aggregates are river gravels, terrace deposits and rock fragments quarried from exposures of rocks such as granites, charnockites, quartzites, sandstones, limestones and marbles, basalts, dolerites and other basic rocks. River borne gravels, most widely used ones, are preferred for concrete aggregates from engineering point of view, particularly when these are well sorted, graded and rounded after long transportation. Because of their rounded nature there is low cement consumption and high degree of bondage.

Coarse aggregate

The distribution of the concrete aggregate in India can be broadly grouped according to their location into three physiographic divisions, namely, (1) Peninsular shield, (2) Extra-Peninsular region and (3) the Indo-Ganga plain. The nature of the construction material and their mode of occurrence widely vary in these three regions. In the Peninsular shield, there is an abundance of rock material suitable for any construction purpose. In the Indo-Ganga plain there is only a limited supply of river borne material suitable for the construction works. In the Extra-Peninsular region construction materials of various types are available ranging from river gravels, terrace deposits exposures of sheet rock but only in limited quantities.

In the Peninsular shield, Pre-Cambrian rocks are most abundant and include metamorphic rocks such as gneisses, granites, charnockites and quartzites which are ideally suited for use as construction material. Some of the sandstone beds belonging to the Cuddapah and Vindyan System are also immensely suitable. The Gondwana sedimentary rocks are not normally suitable but can be used to a limited extent in earth and rock-fill dams as rip-rap. The Rajmahal Traps are one of the most widely used construction material in West Bengal and parts of Bihar. The Deccan Traps, exposed over extensive areas of the peninsular shield are usually hard and durable, but may contain excessive deleterious material like chloropheite, volcanic glass, cherts etc.,. These may cause alkali reaction with the cement and damage the concrete after it is set. Hence careful petrographic analyses of the Traps are necessary, before their use as coarse aggregate.

In Indo-Ganga plain, only river borne gravels are available in a small quantity. In most of the cases where major construction work has been taken up in the alluvial plain, the coarse aggregate have been brought from peninsular shield.

In the Extra-Peninsular region metamorphic rocks such as gneisses, and quartzites are available, in limited quantities, which are generally suitable as coarse aggregate. Tertiary sedimentaries except certain hard sandstone do not possess the required strength nor are sound and durable. Hence, while there is no problem of getting the requisite quantity of coarse aggregate, any engineering project in this region needs careful examination regarding the suitability of the construction material.

Fine aggregate

In India, river sands are commonly used as fine aggregate. Only in

rare cases where suitable sands are not available in required quantity, crushed rocks, or a mixture of crushed rocks and river sands are used.

Sand to be utilised as fine aggregate should consist of hard, durable, oncoated rock fragments. The percentage of the deleterious substance which includes shale, coal, clay lump and alkali mica etc. should be less than 5. Sands should be dense and the specific gravity should be more than 2.6. The loss by weight in five cycles of sodium sulphate test for soundness should not exceed 8%.

Sands for projects in the peninsular shield are generally collected from the river beds. For example, the sands for the D.V.C. dams were invariably drawn from the river beds of Damodar and its tributaries. These sands have been found to be one of the best fine aggregates available in the country.

River sands in the Extra-Peninsular region are always finer, with a higher mica content. Sands used for the construction of Little Rangit project shows presence of silt and clay to the extent of 3.4% and mica 13.8%. Hence crushed quartzites were blended with the natural sand for preparation of the fine aggregate. Similarly, the sands for Kosi dam are found to contain clay and silt 2.4% and mica 8.5%. Hence it was recommended to blend crushed quartzite and Nahan sandstone with the natural river sands. In some cases, for example in Umiam project in Assam, the quality of sand was improved by washing. Elsewhere in Assam, fine aggregates have been obtained by crushing quartzites and sandstone bands and washing them.

The rivers in the Indo-Ganga plain do not contain suitable sand shoals and, therefore, it has either to be brought from the outside sources or have to be obtained by washing the weathered rocks as is being done near Delhi.

Types of Aggregates and Their Usage in Various Projects

River Gravels

Kosi Project : For the construction of the Kosi dam, detailed investigations of the gravel deposits were carried out. Here the gravels are poorly sorted and mainly comprise biotite-gneiss, quartz-sericite schist, injection gneiss, garnetiferous-gneiss, porphyritic granite and slate. Gravels are sub-rounded to rounded and occasionally ellipsoidal. In addition to the river gravels, gravels and boulders available in the terraces consist of similar rock types (Jain, 1952).

Petrographically, the gravels of the different sizes can be classified as follows :

Size Range (cm)	Nahan Sandstones (Per cent)	Granite gneiss (Per cent)	Quartzite (Per cent)	Phyllite (Per cent)	Injection gneiss (Per cent)	Rest (Per cent)
1.27— 2.54	19	38	17	22	2	3
2.54— 5.08	19	42	16	18	2	3
5.08— 7.62	18	40	16	18	3	5
7.62—10.16	19	44	16	13	3	5
10.16—12.70	19	48	22	6	2	3
Above 12.70	16	46	18	14	2	7
Average	18	43	18	14	2	4

Physical properties of the gravels derived from the different varieties of the rocks are tabulated below :

Type of material	Sp. Gravity	Absorption (%)	Compressive strength lbs/sq. in dry	Compressive strength after 72 hours impression	Soundness 10 cycles (% loss)	L.A. Abrasion 500 revolu. %
Nahan sandstone	2.59	2.003	11,160 (706 kg/ sq. cm.)	7,482 (400 kg/ sq. cm.)	100	60
Mica schists	2.57	2.988	8,900 (626 kg/ sq. cm.)	2,505 (176 kg/ sq. cm.)	100	89
			Crushing Strength (Loss Percentage).			
Quartzite (from Tribeni)	2.67	0.303	10.90		0.21	20.40
Quartzite (from dam site)	2.69	0.14	7.43		Nil	14.20
Kokha dolomite	2.833	0.187	8.98		Nil	17.50

Gumti Project, Tripura : Argillaceous sandstones belonging to the Surma Series of Tertiary age are the rock types exposed around the dam site. The sandstones are soft and friable, interbanded with fissile shale bands. The rocks show high absorption varying between 6.98 and 9%, low specific gravity ranging between 2.23 and 2.38 and inadequate crushing strength of 0.5 kg/cm². There is 100% loss in three cycles, during sodium sulphate soundness test (Ray, 1967).

Embedded within the argillaceous sandstones are large concretions of hard calcareous sandstone, which get accumulated in the river and stream beds when the surrounding softer rocks are weathered and are washed away. Hard and fresh boulders of calcareous sandstones vary in size from 15 cm to 1.5 m. in diameter.

Physical properties of the calcareous sandstones are summarised below :—

Type of material	Sp. Gravity	Absorption (Percentage)	Soundness loss in 5 cycles (loss Percent)	Impact value
Sandstone (boulder from Gumti)	2.66	1.25	0.38	5.44
„ (boulder from Lebachera)	2.68-2.71	0.068	0.38	5.50-5.70
„ (boulder from Mailakchera)	2.66	1.08	0.86	—
„ (boulders from Teshemachara)	2.66	1.33	1.67	10.22

The boulders are very sparsely distributed in the stream beds. Their quantity is very meagre, constituting less than 50% of the total requirement of coarse aggregate. Hence the dam has been designed with a casing made up of concrete with calcareous sandstone as coarse aggregates and a shell of brick concrete, where slightly overburned bricks will be used as coarse aggregate. The bricks can be manufactured from locally available sandy soil.

Other Projects of Assam and North Bengal : The concrete dam of the Umiam hydel project in Assam, was constructed of river gravels comprising quartzites and epidiorites (Karunakaran, 1959). Gravels and boulders of quartzite from Little Rangit River were exclusively used

for the construction of the Little Rangit hydel scheme in West Bengal (Choudhury 1965, 66). The quartzites here are dense, with a specific gravity of 2.85, low absorption of 0.97% and high crushing value of 28.53%.

Shingles from the Jaldhaka and Murty rivers were used extensively as coarse aggregate in the Jaldhaka hydel project in West Bengal. Petrographic analysis of the shingle from Murty river shows the following classification : Quartzite 34.8%; blue quartz 12.2%; phyllite 21%; gneiss 22.5%; mica schist 9.4%. The Jaldhaka shingles show the following assemblage : Granite gneiss 49.7%; mica schist 38.7% and quartzite 11.8%.

The physical tests performed on these shingles yielded results, summed up hereunder :—

	Murty shingles	Jaldhaka shingles
Specific gravity	2.72	2.77
Absorption	0.347%	0.602%
Crushing value (%) dry	21.5	22.8
„ 72 hours imprsion	22.0	23.6
Loss in soundness test (5 cycles)	Negligible	Negligible

Shingles from both Jaldhaka and Murty rivers were found to be suitable as coarse aggregates ; yet Murty shingles were used in larger quantities as these were well graded and rounded, and was hence used without any crushing or grading (Choudhury—personal communication).

Terrace deposits.

Bhakra project, Punjab : Gravels and sands available in the terraces have been utilised in many projects of the Extra-Peninsular area. For the construction of the Bhakra dam, Punjab, terrace deposits from Neilla terrace and Fatehwal *khad* terraces have been used (Misra, 1953).

The terrace deposits at Bhakra project comprise boulders of quartzite, sandstone and limestone. These are hard, fresh and compact. Quartzite makes about 85% of the entire mass while percentage of the deleterious materials is only about 1.5%. Specific gravity of this aggregate material varies between 2.66 and 2.87.

Fine aggregates for the Bhakra project were also drawn from the terrace deposits. These are predominantly made of quartz and quartzite. Other constituents include limestone, mica, chert, garnet, zircon, magnetite, chlorite, limonite and felspar in small proportions. The chemically deleterious material like flint, chert and chalcedony ranges between 1.17 and 1.63 percent. The percentage of the physically unsound material is 3.66, which is well within the acceptable limit. The sand is rather high in fines with a fineness modulous of 2, which has been improved by washing and screening.

Beas dam project, H. P. : Mostly quartzite boulders and gravels from the terrace deposits and from Siba *Khad* are being utilised as coarse aggregates for the construction of concrete structures (Chibber, 1968). In this material, the chert and flint particles form only 1.05 per cent. Sound material forms 82—90% of the aggregate, with unsound material forming between 5—7 percent. The concrete used in the tunnels lining ranges in strength from 140, 210 and 280 kg/sq. cm. (2,000, 3,000 and 4,000 p.s.i.).

The seived sand samples from these sources contain 1% to 1.5% of mica in coarser fraction and 3%—10% in finer fractions.

Aggregate from rock types quarried from exposures

Charnockites : The charnockite suite, with variation in composition from acid to ultrabasic, (the intermediate type being the most common,) are characterised by hypersthene. They are bluish grey to dark grey in colour, granitoid and massive. The acid and intermediate members contain bluish grey quartz containing accicular inclusions of rutile, and perthitic microcline and plagioclase. Garnet, zircon, magnetite and limenite are usual accessories. The basic variety is noritic and rich in hypersthene. The ultrabasic ones are pyroxinites and hypersthenites. The specific gravity of the various types varies from 2.67 to 3.37. The fresh rocks are hard and durable and form very good aggregate material. The charnockites are widely distributed in the Peninsular India and are being extensively used as concrete aggregate and masonry blocks in various projects of South India and Orissa.

Granites and Gneisses : Fresh granites are one of the most commonly used rock as concrete aggregate and dimension stone. Granites and gneisses are exposed extensively in Peninsular and Extra-Peninsular area. The rocks are hard and durable and usually dense with specific gravity more than 2.6. The water absorption in the fresh granites are normally less than 1% and the compressive strength of granite is usually more than 25,000 p.s.i. (1758 kg/sq. cm.).

Granites and gneisses have been used for the construction of the dams of D.V.C. project. The physical properties of the some of the gneisses used as coarse aggregate in the Panchet dam, Bihar, are tabulated below :—

Type of Granite	Specific gravity	Absorption %	Crushing strength (kg/cm^2) dry	Crushing strength (kg/cm^2) after 72 hours immersion
Biotite-granite	2.69	0.24	211.6	211.6
Garnetiferous gneiss	2.70	0.54	281.9	70.3
Gneiss with quartz vein	2.62	nil	211.6	152.2
Hornblende gneiss	2.92	0.11	211.6	140.6
Fine-grained gneiss	2.92	0.17	352.2	352.2

Granulites have also been used in Panchet dam which show much higher strength.

Pink granite and gneisses are being used for the construction of the Tenughat dam in Bihar. The specific gravity of the granite is 2.62, absorption 0.272%; attrition loss 6.75%; soundness test loss 1.25% in five cycles and a crushing value 29.2% (B.B. Test).

Porphyritic granites exposed near the dam site of the Kopili hydel project, Assam, were tested for their suitability as coarse aggregate. These have a specific gravity of 2.62 and absorption only 0.47%.

Gneisses have been used as coarse aggregates in the construction of Getalsud dam, Bihar (Bansode, 1968). The physical properties of these gneisses enumerated below :—

Rock type	Specific Gravity	Absorption (Per cent)	Comperative Strength dry ($kg./m^2$)
Coarse grained hypersthene gneiss	2.76	0.06	1856
Medium ,, ,, ,,	2.70	0.34	—
Medium grained gneiss	2.70	0.34	—
Coarse grained gneiss	2.63	0.15	715

Calc.-gneiss and granites exposed near the dam site of the Sabarmathi project, Gujarat, were found fit for use as masonry blocks and concrete aggregate (Basu, 1953). The samples collected from the nearby areas such as Kesampar hills, Dhomosi hills and Bania-ka-Tekri gave the following results :

Site	Specific Gravity	Absorption (Percent)	Soundness % loss in 10 cycles
Kesampus	2.705	0.196	0.91
Bania ka Tekri	2.734	0.5481	—
Dhomosi hill	2.62	0.53	0.94
Boulder from river	2.741	0.2777	—

Hornblende-gneisses were used as coarse aggregate during the construction of Maithon dam, D.V.C., Bihar (Mitra, 1952 and Venkatraman, 1951). The crushed pieces have conchoidal to irregular fractures and there are not much fines. Micaceous minerals are absent. Apart from hornblende-gneiss, medium grained, acid granulitic gneisses were also used. The gneisses break into angular pieces because of suitable disposition of the foliation and joints, with an economic out turn for the unit weight of explosive used.

Gneisses have also been used for the construction of Hirakud dam, Orissa (Krishnaswamy and Basu, 1954). These gneisses have a bearing strength of 15.75 to 17.35 kg/sq. mm.

Source	Properties of Aggregate at Hirakud Project				Loss Angles Abrasion test (percent loss 500 revolutions)
	Type	Sp. gravity	Present absorption	B.S. crushing test (percent loss)	
1. Silipathar	Granitic gneiss	2.709	0.24	15.7	17.33
2. Latchmi Dungri	Granitic gneiss	2.814	0.17	15.1	17.12

However, some of the younger porphyritic gneisses of this area were proved by X-ray defraction studies to contain Jarosite, a basic sulphate of potassium and iron which guided rapid deterioration of rock on exposures. Hence these younger gneisses were not considered to be suitable as concrete aggregate.

For the proposed Pancheshwar dam in U.P. granite-gneisses were recommended for use as concrete aggregate. These gneisses were tested and found suitable (Mandwal and Agarwal, 1968). The test results are as below :—

Water absorption	—	1% — 1.67%
Specific gravity	—	2.5 — 2.85
Crushing value	—	38.3% — 54.1%
Abrasion value	—	39.2% — 56.6%
Reduction in alkalinity	—	30—260 R.C. per litre

Basic rocks : The most common variety of coarse aggregates in Western India for the construction purposes are the Deccan Trap (basalt). Massive, dense, hard and durable Deccan Trap rocks and dolerites occurring as dykes are used extensively as road metals and concrete aggregates. Sometimes it contains deleterious minerals like chlorophaeites, volcanic glass, chert etc. Hence materials for the concrete aggregates should be carefully selected and tested petrographically to avoid any possibility of alkali aggregate reaction. Koyna dam of Maharashtra was constructed with basalts as coarse aggregate.

Samples from Deccan Trap flows collected from Bansa area have been analysed and petrographically grouped into four types (Parthasarathy, *et.al* 1968). The physical properties of the different types of the rocks encountered in the Deccan Trap flows are summarised below :

Type of rock	Sp. gravity	Absorption (Percent)	Compressive Strength (kg/sq. cm.)
Amygdalcidal Basalt	2.89 to 2.87	0.237	2109
(Plagioclase felspar 35%, Pyroxene 27%, Opaque 34%).			
Basalt (Plag. felspar 42%, Pyroxene 27%, Opaque 28%, Glass 3%)	2.47 to 2.85	4.49 to 0.68	1335
Felsites. (Felspar 50%, Quartz 19%, Ferromagnesian min. 13%, Opaque 14%, Glass 4%).	2.47 2.50	3.21 4.31	2109
Tuff.	2.30	3.95	

Massive basalts are proposed to be used in the spillway of a 44.9 m. high earth dam across Tulsi river near Burambali, Kolhapur district Maharashtra. The crushing strength of these basalts under saturated condition varies from 1081 to 212 kg/cm^2. Specific gravity of the basalts ranges between 2.85 and 2.93. Massive basalts will also be used for the construction of the spillway of the Viroli dam in Maharashtra.

The country rock around the Ukai project in Maharashtra is amygdaloidal basalt, the amygdales being either zeolites or cryptocrystalline silica. As such these rocks are unsuitable as aggregate in cement concrete because of the possibility of alkali-aggregate reaction (Mahendra, 1963). However, these rocks have been used as rip-rap. These coarse grained dolerites occurring as dykes flanking the basalts can be used as coarse aggregate. The dolerites are hard and sound and do not show any alteration of the minerals. The constituent minerals are plagioclase felspar and augite and exhibit an ophitic to sub-ophitic texture. Gabbro-diorites available near the dam site is also suitable for use as coarse aggregate.

Rajmahal Traps in Bihar, are being extensively used in various construction projects in Eastern India. In fact 'Pakur stones' the local name of the Trap rocks are one of the best road metals. At the Farrakka barrage in West Bengal, Rajmahal traps are being exclusively used as concrete aggregate (Basu, 1962). The rocks are medium to fine grained and extremely hard and contain mainly labradorite and augite (pigeonite) and opaque minerals. The total percentage of the deleterious materials including glass, plagonite, chlorophaeite, chalacedony etc. is less than five.

Amphibolite : Amphibolite is a very commonly used rock for construction purpose. Amphibolite used in the construction of Getalsud dam, Bihar, shows that the rocks are abnormally hard and dense. Specific gravity of the rock exceeds 3.1, absorption is only 0.04% and the compressive strength is also abnormally high. Because of their higher density, the cement consumption is somewhat higher in these cases.

Quartzites and sandstones : Quartzite is one of the most commonly used aggregate material in India. Quartzites belonging to Cuddapah system were used as concrete aggregate for the construction of Rihand dam in Uttar Pradesh (Rao, 1968). Specific gravity of these quartzites was 2.682 and absorption 0.16%. The average crushing strength was 1822 kg/sq. cm. Quartzites have also been used as concrete aggregate in the construction of power dam section of Hirakud dam project, Nagarjunasagar and Srisailam projects of Andhra Pradesh. The result of a few tests on the quartzite aggregate of Hirakud dam project are tabulated below :

Type	Specific Gravity	Absorption (Percent)	B.S. Crushing value (percent loss)		Crushing strength tons/sq. in		Los Angles Abrasion test percent loss (500 revolutions)
			Dry	After 72 hrs. soaking in water	Dry	After 72 hrs. soaking in water	
Quartzite (river stringle)	2.665	0.30	24.1	—	—	—	39.20
Quartzite	2.749	0.45	21.0	19.0	10.21	—	—
Weathered quartzite.	2.658	1.34	35.2	38.9	2.58	1.95	—

Kaimur quartzitic sandstones are proposed to be used as rip-rap and masonry stone for the construction of Kuria dam of Kasiary project, in Rewa district, Madhya Pradesh (Jain, personal communication). The quartzitic sandstones are fine grained and whitish grey to ligh olive in colour.

Some of the tests carried out on the fresh Kaimur quartzitic sandstone are tabulated below :—

Sl. No.	Density (kg/cm.)	Absorption (Weight Percent)	Static modulus of elasticity (10^3 kg/cm^2)		Compressive Strength (kg/sq. mm.)	
			dry	wet	dry	wet
1	2.482	1.18	81.91	45.28	8.09	7.84
2	2.482	0.85	71.36	27.42	13.51	7.32
3	2.482	1.94	132.88	99.13	13.06	7.37

The test results indicate that the physical properties of these sandstones are not uniform, probably due to variation in granularity, nature of cementation, grading and degree of packing of the grains constituting the rocks.

The pink coloured massive Bhander sandstones are proposed to be used for the construction of a dam across Narmada river in Madhya Pradesh. Bhander sandstones are proposed to be used as rip-rap and

masonry stone for the construction of dam under the Ken project. The sandstones are hard and dense with density of about 3.40 kg/cm. The absorption of 72 hours varies from 1.12 to 1.64% by weight. The compressive stiength under saturated condition varies from 8.81 to 12.37 kg/sq. mm. Cream and white coloured massive sandstone of Kheinjua stage (L. Vindhyan) are proposed to be used for the construction of 83 m. high concrete dam for Banasagar project.

Boulders of Oligocene sandstone, called the Barail sandstone have been extensively used as coarse aggregates for the construction of concrete and reinforced concrete structures in Upper Assam. The Oil India installations at Dulaijan, Naharkhatiya, and the thermal power station at Naharkatiya are some of the more important structures have been built out of this material, besides all the major bridges on N.H. 34. Some of the lower Eocene sandstones from the proposed Kopili dam site area, Assam, shows crushing strength between 175 kg/cm^2 to 513 kg/cm^2 and breaking load between 3.04 tons to 11.47 tons (Mehta, 1959).

Limestone : Limestones are rarely used as concrete aggregate in India. Kopili Project, Assam, which is located in a limestone terrain, may be constructed using limestone as concrete aggregate. The limestones here has a specific gravity of 2.65, absorption of 1.17% by wt., and a crushing strength of 2200 kg/sq. cm. At the Dhiangarh hydel project, J and K, the chemical reactivity tests carried out on the dolomite have shown inoncuous results. If the mortar bar test also gives favourable results then the non-cherty bands of dolomites will be used in the concrete at the Dhiangarh hydel project (Ashraf and Tiku 1968).

Dolomitic limestones have been used as concrete aggregate for the construction of Mandira dam, Orissa. Aggregates were quarried from Kansbahal and Amghat, of which limestones from Kansbahal were considered to be more suitable and these were mainly used. (Mandira Dam Project, Final Report, 1959).

Location of quarry	Specific Gravity	Absorption	Impact test (loss percent)	L.A. abrasion test loss percent	Soundness loss percent
Kansbahal	2.76	0.26	24.44	33.9	0.33
Amghat	2.75	0.25	34.5	43.7	1.8

Pozzolanic Materials in India

A pozzolana is a siliceous or aluminous substance, and may be either natural or artificial. Natural pozzolanas are volcanic ashes, tuffs and diatomaceous earth. Some clays and shales can be converted to pozzolanas by calcination. Fly ash is an artificial pozzolana produced as an industrial by-product. Rhyolites zeolites are also known to possess pozzolanic properties.

Various geological formations in different parts of the country are sources of good pozzolanas which are enumerated below (Hazra and Krishnaswamy 1953) :—

Northern India : Tertiary shales and clays, acid volcanic rocks of Pir Panjal ; fuller's earth and bentonites in Jammu and Kashmir State, Gondwana shales of the Singrauli coal field in Mirzapur district and phyllites in the vicinity of Rihand dam, U.P. Tertiary and younger shales, Punjab Himalayas ; fuller's earth and bentonites of Bikaner ; Eocene shales and clays of Jaisalmer and Palana areas, and tuff beds of Malani and Jodhpur areas of Rajasthan, are some of the pozzolanas occurring in northern India.

Eastern India : Gondwana clay and shales ; Cuddapah shales ; glassy flows of Rajmahal traps, lithomargic deposits of Ranchi plateau ; tuffs in the Iron Ore Series and Dhanjori and Dalma volcanics ; volcanic ash and pumicite of Barren and Nicobar Islands ; phyllites of Gangpur series ; diatomaceous earth, Tertiary shales and clay and Radiolrian cherts of Andaman and Nicobar Islands, are the pozzolanas of Eastern India.

Southern India : In the peninsular area, Tertiary and Jurassic shales and calys ; Vindhyan and Cuddapah shales ; tuffs and ash beds in Deccan Traps ; rhyolites, lithomarges and ochres occurring below bauxites in Katni and other areas, are used as pozzolanas.

Pozzolanas have been used in India as a substitute for cement for a long time. In many major engineering structures, such as for the construction of Bhakra Dam, Punjab, Dagshai shales which contains kaolinite have been used as pozzolana to substitute the portland cement partly. At the Hirakud Project, Orissa, China clay, phyllite, carbon phyllite and Surkhi obtained by calcining the local soil were considered for use as pozzolana in cement, but the Talabira Clay was found to be more active, which were actually used.

Construction Materials for Earth and Rock-fill Dams

Material for core and shale zones

Huge quantities of construction materials are required for the earth and rock-fill dams. Sufficient quantities of the material with ideal characteristics may not be always available at the proposed site and, therefore, the type and the design of the dam has to be adopted according to the construction materials available. A few projects, where the geological investigations on the construction materials have played a significant role in the design and construction of the dam are discussed below.

Beas dam project, Himachal Pradesh : For the construction of Beas dam, the investigations indicated the absence of any single source of thick suitable earth and rock-fill material. Therefore, the dam has been so designed that a mixture of 50% crushed sand rock with 50% clay-shale could be used in the core section of the dam with proper compaction, so as to get a satisfactory density of the material. After conducting the relevant laboratory studies of the sand-rock available at the Beas dam-site, the following properties of the material were found acceptable (Memo No. 79-BSD, 1964).

i)	Unit dry weight	—	1.875 gm/cm^3
ii)	Unit moist weight	—	2.080 gm/cm^3
iii)	Unit saturated weight	—	2.168 gm/cm^3
iv)	Unit submerged weight	—	1.168 gm/cm^3
v)	Permeability	—	10^{-5} to 10^{-6} cm/sec.
vi)	Cohesion (c)	—	0
vii)	Angle of internal friction	—	30°

Ramganga dam project, U.P. : For the core and the shell section of the Ramganga dam the Middle Siwalik clay shales and sand rock obtained from the structural excavations and from the exposures would be used. The flood plain deposits (Ramnagar clays) and Upper Siwalik (Dun ?) clays lying north of Boxar were also investigated. With following results.

Soil property	Ramnagar clays	Up. Siwalik (Dun ?) clays
Liquid limit	19.2 — 34.6	22.7 — 34.6
Plastic limit	14.8 — 21.6	14.1 — 19.8
Plasticity Index	1.2 — 18.55	8 — 18
Angle of internal friction	18° — 35.5°	
Cohesion 'c'	14,408 — 23,826 kg/m^2	

Rip-rap material

The material required for the rip-rap in an earth and rock-fill dam should be of large size, hard, tough and durable. Generally the large size boulders in the river bed deposit, if available are used. In case river boulders are not available, the hard rocks or concrete blocks may be used as rip-rap.

At the Ramganga dam site, the Lower Siwalik sandstones of the area have the compressive strength less than 210 kg/cm² against the desirable compressive strength of the order of 350 kg/cm². The rip-rap material for the dam has to be either brought from a distance or obtained by screening the terrace deposits. Similarly for the proposed Thein dam project in Punjab, the material shall have to be quarried from the Lower Siwalik sandstones of the area or obtained by excavating and screening the Upper Siwalik boulder beds exposed a few kms. downstream of the dam site (Jalote & Jaiswar, 1963).

Concluding Remarks

Construction materials are widely distributed, both geologically and geographically. Some knowledge of the properties of materials in an area would help a lot in the proper planning, preliminary design and determination of the feasibility of a project. So far the lack of engineering geology laboratory in the Geological Survey of India the geologists have to depend on the data supplied by the engineers and they do not get sufficient first hand experience to correlate the behaviour of the rock in the laboratory with that in the field.

To cope up with above problem it has been decided to have a material testing and Rock Mechanics laboratory within the Department where the geologist will have an opportunity for testing the materials for determining their physical and mechanical properties. The systematic studies carried out in this laboratory on the major rock types distributed in the country would go a long way in the preparation of the construction material map of the country which would be immensely useful to the engineers and geologists in planning engineering projects.

REFERENCES

Ashraf, Z. and Tiku, A. K. 1968.—Progress report No. 3 on the preliminary geological investigations for the Salal Hydel Project, Udhampur district, J and K State, *Rep. Geol. Surv. Ind.* (unpublished).

Bansode, R. B., Sarkar, B. and Basu, S. 1968.—A geotechnical report on the construction stage investigations of Getalsud Dam, Subarnarekha Hydel-cum-Water Supply Project, Ranchi district, *Rep. Geol. Surv. Ind.* (unpublished).

BASU, S. 1962.—A note on the Farakka Barrage Project, Murshidabad and Malda Districts, West Bengal, *Rep. Geol. Surv. Ind.* (unpublished).

———— 1953.—A geological report on the Sabarmati Project, Mehsana District, Gujarat. *Rep. Geol. Surv. Ind.* (unpublished).

CHIBBER, I. B. 1968.—A petrographic report on the samples of coarse and fine aggregates from the Siba Khad and Sathana area, Beas Dam Project, Himachal Pradesh, *Rep. Geol. Surv. Ind.* (unpublished).

CHOWDHURY, A. K. 1965, 66.—A note on the further geological investigations of Little Rangit Scheme, Darjeeling District, West Bengal, *Rep. Geol. Surv. Ind.* (unpublished).

HAZRA, P. C. AND KRISHNASWAMY, V. S. 1953.—Natural Pozzolanas in India, their utility, distribution and petrography. *Rec. Geol. Surv. Ind.* Vol. 87, Pt. 2.

JALOTE, S. P. AND JAISWAR, H. P. 1963.—Progress report on the geological investigations tor the Thein Dam Project, Ravi river, East Punjab, conducted during the field season 1962-63, *Rep Geol. Surv. Ind.* (unpublished).

JAIN, M. S. 1952.—A report on the concrete aggregates near Chhatra, Kosi Project, Nepal, *Rep. Geol. Surv. Ind.* (unpublished)

MINISTRY OF IRRIGATION AND POWER. 1959—Mandira Dam Project. Final Report 1959

IRRIGATION DEPARTMENT, PUNJAB.—Bhakra and Beas Dams Organisation, Kakanagar, New Delhi Memo. No. 79, BSD.

KARUNAAKARAN, C. 1959.—Preliminary report on investigations of the Umiám-Barapani Hydro-electric Project, Assam, *Rep. Geol. Surv. Ind.* (unpublished).

KRISHNASWAMY, V. S. AND BASU, M. C. 1950.—Thier interrim report on the detailed geological investigations concerning the Hirakud Dam Project. *Rep. Geol. Surv. Ind.* (unpublished).

MAHENDRA, A. R. 1963.—Progress report on the geological investigations carried out at Ukai dam site, Surat District, Gujarat. *Rep. Geol. Surv. Ind.* (unpublished).

MANDWAL, N. K. AND AGARWAL, A. N. 1968.—Progress report No. 3 on the geological investigations for the Pancheshwar dam site, District Almora, U. P., *Rep. Geol. Surv. Ind.* (unpublished).

MEHTA, P. N. 1959.—A geological report on the Kopili dam site, K and J Hill district, Assam, *Rep. Geol. Surv. Ind.* (unpublished)

MISRA, S. S. 1953.—Report on the petrographic examination of aggregate material from Fatehwal Khad area, Bhakra Dam Project, Punjab, *Rep. Geol. Surv. Ind.* (unpublished).

MITRA, A. 1952.—A geological report on the Panchet hill dam site, D. V. C. *Rep. Geol. Surv. Ind.* (unpublished).

PARTHASARTHY, A., PATWARDHAN, A. S. AND OKA, S. S. 1968.—Physical and Engineering Properties of Certain Volcanic Rocks and their influence on the Design Aspects of Flexible Road and Air-Port Pavements., *Jour. Ind. Soc. Eng. Geol.*, Vol. III, No. 1.

RAO, G. S. M. 1968.—Coarse aggregates for Rihand Project, Mirzapur District, U. P., *Jour. Ind. Soc.*, of *Eng. Geol.* Vol. III, No. 1.

RAY, S. 1967.—A note on the availability of construction material for the Gumti Hydel Project, Tripura, *Rep. Geol. Surv. Ind.* (unpublished).

VENKATARAMAN, D. 1951.—Coarse aggregates material for Maithon Dam, D. V. C., *Rep. Geol. Surv. Ind.* (unpublished).

GROUNDWATER

BASIN-WISE SYSTEMATIC GEOHYDROLOGICAL STUDIES BY THE GEOLOGICAL SURVEY OF INDIA—A REVIEW

by

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Introduction

The "hydrological cycle" is by far the most vital natural phenomenon which controls the environment of the mankind and existence of organic world. The development of human civilization, science and technology depended on water availability in the most fundamental manner. The motive force of scientific endeavour of man has been the urge to know the unknown, and to comprehend the elements of nature. In this pursuit of man his enterprise in understanding the life sustaining phenomenon of "hydrological cycle" should naturally be very important. However, the magnificiant achievements in physical sciences not-withstanding, his comprehension of the realm of water in the earth has not been as spectacular. While natural abundance of life sustaining water gave rise to a general sense of complacency in him till the last century in such areas where water aplenty was available for his use, the populace in scarcity areas tended to migrate to areas of easy water availability, this being the simplest solution in none too densely populated continents on the globe. Thus development of early river valley civilizations and concentration of population had been the well established demographic pattern. By the turn of the 18th century the population pressure grew in the major river valleys and migration to all continents became a real necessity. The ninteenth century socio-political evolution gave rise to modern nation States of unlimited soveriegnty and like all other material resources the realm of water resources remain today bounded by political boundaries, however irrational or unscientific such division might be.

The impediments caused by man's own action in evolving a socio-political order all the same compelled him to give more thought for water resources due to the geometric growth rate of demand for water. Beginning with a few hydro-scientists of early twentieth century, this consciousness regarding water resources led to the development of the science of hydrology as we see today. Till the thirties of this century the hydrological studies were rather restricted to piecemeal regional studies. Soon it

was realised that a rational assessment of water resources and their development for use on local scale would not provide the right answer. The comprehensive assessment of water resources within a given geomorphic unit or basin in its entireity is now accepted by all hydro-scientists as the most rational approach. The United Nations (1953) published a monograph on comprehensive basin-wise studies on water resource and this made significant contribution in guiding hydrological studies in a rational perspective, particularly in the under-developed countries.

In India, eminent scientists realized the need for such comprehensive studies but till Independence the attempts in this regard were somewhat purfunctory. The development of water resources, particularly surface water resources in the major river valleys, had been going on and large areas were brought under irrigation by using surface water. The irrigation canal network built in the Punjab, and Sind (now in Pakistan), the Ganga alluvial plain, and in the East coastal plains bear testimony to these water resources development programmes. These are regions where surface water resources were available in plenty and many of these irrigation network were built even without carrying out any intensive hydrological surveys. Post-construction surveys were also not often given the priority that they deserved. Thus acute problems in water resources and land management cropped up after a few decades, particularly in the Punjab. Surface water development exclusive of the assessment of its relation to the regime of underground water led to complex management problems such as extensive water logging and extensive land salinisation. The deleterious trends were in sight well within the decade of the thirties but all out scientific assessment of the problem and solution thereto remains to be done even today. The reason obviously lies in lack of comprehension of the problem on one hand and paucity of resources for investment in hydrological surveys on the other.

The acute economic problem of additional food production following the dismemberment of pre-1947 India forced the national government to lay emphasis on immediate development of water resources in all basins having such potentialities so that larger areas can be irrigated for raising food crops, rather than to undertake an all out comprehensive assessment of water resources prior to taking up developmental programmes. The dilema was indeed too critical at that juncture and large investments in development prior to thorough appraisal of resources was justified.

Hydrological surveys for assessment of water resources are directly linked up with varied scientific disciplines, and for the studies to be useful co-ordination of the collection of scientific information by all the related

fields is essential. The primary surveys include geomorphic and topographical surveys, meteorological observations at statistically controlled observation points, geological studies in relation to surface and groundwater regimes, and applied hydrological studies to make an inventory of water resources potential, and existing stage of consumption.

In India topographical and geomorphic surveys are functions of the Survey of India, the meteorological observations are made by the Indian Meteorological department, the surface water resources surveys are primarily conducted by the Central Water and Power Commission and in some cases by various State Departments as well, while for the survey of consumption of water resources no single organisation or department is specifically responsible. Such departments as Irrigation and Water ways, Public Health Engineering, Agriculture, etc., under the various State Governments collect some data on water consumption within their respective States. There again the data collection is not guided by any uniform standard procedure or norms so that scientific utility of data have wide variations. In this given set up a proper inventory of water consumption is extremely difficult.

Background of Basin-wise Survey of Groundwater in India

The first geologist of the Geological Survey was appointed in 1846 and by the fifties of the last century the Geological Survey of India was an organised Survey department though with very little man-power. Sporadic groundwater surveys for specific water supply needs had been taken up by the Survey as early as 1869 (Medlicott. Rec. G.S.I., Vol. 2, pt. 2). Six year later a report was published by W. T. Blanford (Rec. G.S.I., Vol. 8, pt. 2) on water bearing strata of Surat district, Gujarat. In the next ten years problem to find groundwater for irrigation was received much attention in the Survey and in 1880 W. King (Rec. G.S.I., Vol. 13, pt. 2 and 3) gave an account of 'artesian wells' in Pondicherry area while H. B. Medlicott wrote a note on artesian borings in India (Rec. G.S.I., Vol. 14, pt. 3) in 1881. In 1883 an additional landmark was the first ever systematic account of the thermal springs of India by T. Holland (Mem. G.S.I. Vol. 19, pt. 2). In the same year Captain J. Clibborn wrote a brief account of 'Irrigation from wells in the North-western provinces and Oudh' (Rec. G.S.I. Vol. 16, pt. 4). The quest for artesian wells, (which made headlines in news due to discovery of large artesian field in Australia at that time) were still uppermost in the minds of H.B. Medlicott and R. D. Oldham and they recorded 'Further considerations upon Artesian sources in the plains of Upper India' and 'Memorandum on the probability of obtaining water by means of artesian wells in the plains of Upper

India' respectively in 1885 (Rec. G.S.I. Vol. 18, pt. 2). We do not find much activity in groundwater studies till 1901 except for a note on 'Recent artesian experiments in India by E. Vredenberg in 1901 (Mem. G.S.I. Vol. 32, pt. 1). In 1909 Hayden published an account of the 'thermal springs in Rajmahal Hills' (Rec. G.S.I. Vol. 37, pt. 4). However surveys related with hydrology during the years 1906 and 1910 also had not only been connected with thermal springs but also with very cold springs and run off from glaciers of Northwest Himalaya and Sikkim Himalayas (Rec. G.S.I. Vol. 35, pt. 3 and 4 and Rec. G.S.I. Vol. 40, pt. 1). In the Rec. G.S.I. Vol. 40, we also find an account of lakes of salt range in the Punjab (now in Pakistan). There is not much to mention between 1910 and 1927. In the later year results of a deep boring at Ambala have been published (Rec. G.S.I. Vol. 60, pt. 3) giving some idea of the subsurface geology in the eastern Punjab plains. An account of Glaciers of Karakoram and neighbourhood is seen in 1930 (Rec. G.S.I. Vol. 63, pt. 2).

A significant headway was made in tubewell development in Uttar Pradesh and the Punjab in the thirties of this century on the basis of programme oriented by William Stamp. Stamp worked in collaboration with the Geological Survey of India and earlier reports by Medlicott, Blanford and Oldham were his main forte in preparation of this programme. This was possibly the first ever comprehensive scheme of groundwater development in India, in which, engineers, hydrologists and geologists worked in a co-ordinated manner. This scheme, designated as "the Ganga Valley Tubewells Irrigation Scheme (1936)" led to the installation of 1500 heavy-duty tubewells for irrigating some 30,000 sq. km. in the Ganga basin. Joint venture of engineers and geologists under this scheme led to much experimental work and perhaps laid the course for future trend of hydrological studies. Studies were carried out on the effect of large scale pumping on lowering of water-table, rate of recovery of water level, radius of influence of wells under pumping, determination of safe yield, coefficient of permeability of the aquifer material, etc. From the studies carried out it was concluded that a depression of head by 7 metres, a maximum of 150 cubic metres of water could be safely extracted from a 150 m.m. diameter tubewell tapping 15 to 30 metres of coarse grained aquifer material. The tubewell irrigation scheme in the Punjab were based on the norms thus established. The significance of this programme lies in the fact that for the first time geologists of the Survey and engineers of U.P. Government attempted to make a systematic study of the aquifer hydraulics.

The water supply investigation report for water supply of Peshwar and Mardan districts in the North-West Frontier Province (now in Pakistan) with an appendix on the Kohat valley (Rec. G.S.I. Vol. 74, pt. 2, 1939) though not a comprehensive groundwater assessment report, none-the-less

give a regional account of water resources available for development. In 1940 A. L. Coulson published his water supply papers (Mem. G.S.I., Vol. 76) on 'The Geology and underground water supply of Calcutta, Bengal with special reference to tubewells' (water supply paper No. 1) and 'Water supply of Darrang district, Assam' (water supply paper No. 3) and in both these papers he attempted to present as comprehensive a picture of the local groundwater regimes as the available data would permit. He attempted to establish the geohydrological set up, characteristics of aquifers, a realistic inventory of water consumption, assessment or potential resources, recharge to aquifers, etc. The limitations of data available for such comprehensive evaluation were apparent but the concept of regional assessment of the groundwater regime qualitatively and quantitatively is very well discernible. The period of the Second World War called for varied and extensive water supply investigations for defence requirements and these were taken care of by the specially created Strategic Branch of the Survey. The studies, through the sheer weight of number of investigations and the varied problems of geohydrology in different parts of the country, forced a realization in the Survey that groundwater studies need a Specialist Division. The end of the Second World War in 1945, thus, also marks the beginning of the Specialist Division of Groundwater and Engineering Geology in the Survey.

Since independence of the country there has been rapid expansion of the activites of the Geological Survey of India including its groundwater activities. The years from 1949 to 1953 saw the collaboration of the Groundwater Branch with the same in the United States Geological Survey and a few geohydrologists from the U.S.G.S. were deputed to the Geological Survey A number of collaborative ventures in systematic geohydrological studies were taken up by the U.S.G.S. geologists and the G.S.I. geologists and the reports were published later in the form of Bulletins of G.S.I. (Series B). The collaborative studies between Taylor, Ray, Sett (Groundwater Geology of Pali Region Jodhpur district, Western Rajasthan Bull, Sr. B, G.S.I., No. 6), Taylor and Oza (Geology and Groundwater of the Dudhai area, Eastern Cutch; Bull. Sr. B, G.S.I., No. 5) and Taylor and Pathak (Geology and groundwater resources of Anjar Khedoi Region, E. Cutch with reference to the Kandla Port Water Supply—Bull. G.S.I. Sr. B, No. 11) are significant attempts at regional comprehensive studies on the groundwater regimes of the areas covered. Under assistance from U.S.A. a large programme of tubewell drilling was launched in the States of Punjab, Uttar Pradesh and Bihar during 1950—55, based on experience of the tubewell drilling programme of the thirties to which references, have already been made. These tubewell drilling operations opened up a new horizon for the Groundwater Branch of the Survey. These drilling operations

were utilized for collection of subsurface geological and hydrological data for vast areas. Besides collecting subsurface formation samples, electrical logs were recorded and aquifer performance tests were conducted where-ever possible. The data thus collected laid the beginning of the comprehensive studies of the basin-wise groundwater regimes. In 1952 negotiations were in progress for an Indo-American venture on groundwater exploration in India. Auden (1952) prepared memorandum No. 1 on this project, wherein he demarcated the areas in the major alluvial basins and coastal plains of India which shew promise of large-scale groundwater development. Based on this memorandum the Operational Agreement No. 12 between the Technical Co-operation Mission of U.S.A. and the Government of India was signed for launching the 'All-India Groundwater Exploration Project'. This unique project was the largest of its kind, taken up anywhere in the world. The Geological Survey of India was entrusted with the scientific studies connected with the project and the newly created department *viz.*, Exploratory Tubewells Organisation under the Ministry of Food and Agriculture, Govt. of India, was entrusted with the job of drilling and construction of test wells and production wells under guidance of the Geological Survey of India. To cope up with the stupendous work-load of this project, a new section *viz.*, the Groundwater Exploration Section was created in the Survey in 1954. The Project activities were carried out in the alluvial plains, coastal plains and soft rock areas of all the States of India excepting Jammu and Kashmir and Mysore. The exploration programme was executed in a systematic pattern in the areas covered. Following regional geohydrological reconnaissance and geophysical exploration borehole sites for exploratory tubewells were selected. Exhaustive data of lithological, sedimentological and stratigraphic significance were collected from the exploratory boreholes. Based on these data exploratory tubewells were constructed and hydrological tests were conducted to determine hydraulic parameters of the aquifers encountered. Detailed chemical studies of the groundwater in different aquifers were also undertaken. Following the exploratory drilling and testing operations regional geological and hydrological correlations were made to delimit areas suitable for groundwater development. Extensive areas of the Ganga, Brahmaputra, Sindhu, Narmada, Purna and the Tapti basins, the coastal plains extending from the delta of the Ganga to that of the Kavery in the east and the coastal plain in the west coast of Kerala were covered under this project. Special studies in a very intensive pattern were also carried out in the artesian basin of Neyveli to determine the hydraulic characteristics of the confined aquifers there, with a view to determining the pumping rate necessary to depress the water level below the lignite strata, so that mining becomes feasible. By the middle of 1959 the exploration programme was terminated and the pattern was already set for long-term basin-wise studies of the groundwater regimes.

Basin-wise Studies

Unlike other mineral resources, groundwater is replenishable and on the basis of this fundamentally unique character, its resources assessment, development and utilization call for dynamic programming. Groundwater studies have to be continuous—only the nature of the studies change depending on the stages of exploration, development and utilization. Keeping this perspective in view, the Survey's programme in groundwater activities since 1959 have been oriented towards comprehensive understanding of the groundwater regimes in the different geohydrological zones controlled by geomorphic, geologic and tectonic environments. To begin with areas which were covered under the groundwater exploration programme during 1954—59, were taken up for long term systematic geohydrological studies. Gradually such studies are being extended to other areas with the ultimate objective of covering the entire country.

The systematic groundwater investigations by the five Groundwater Divisions in the respective Regions of the Survey include the following general objectives :

1. The studies will be chiefly directed to prepare the water table maps for the various seasons, assess the groundwater recharge and the mechanism of recharge and to determine the chemical characteristics of the groundwater ;
2. Studies of the relation between surface water and groundwater ;
3. Determination of the hydraulic characteristics of the aquifers ;
4. Study of the problem of saline water invasion into aquifers in the coastal areas ; and
5. Investigation of the problem of water logging in the country.

The Committee on Water Resources set up by the Planning Commission arrived at almost the same conclusions as regards immediate objectives of the study in the field of groundwater. The Commission had recommended for the Third Five year Plan the following nine point programme :—

1. The assessment of the groundwater resources separately for each river basin on the basis of data currently available.
2. The additional measures that are considered necessary for a comprehensive and dependable assessment of the groundwater resources in each river basin and sub-basin.

3. An assessment of the existing quantum of annual utilization of groundwater separately for each river basin and sub-basin for (i) irrigation, (ii) industrial uses and (iii) domestic supplies.

4. An assessment of additional groundwater requirements for the above three items for full development of (a) existing projects, (b) projects currently under execution and (c) committed project, e.g. projects included in the Third Plan but works on which have not begun.

5. The determination of the unutilized groundwater resources in each basin and sub-basin, after meeting the aggregate current utilization and after making a provision for the additional requirements for existing and committed projects.

6. The assessment of the future utilization of the surplus groundwater resources in each basin and sub-basin with due consideration for the recharge and depletion of the groundwater table.

7. Complication of currently available data regarding behaviour of groundwater table in different basins and sub-basins, because of the necessity for having these data recorded and collected in a systematic and standardised manner, to enable a study of the year to year fluctuations and of the general behaviour of the groundwater table in different river basins.

8. An assessment on the basis of the above studies of the ultimate utilization and of surplus groundwater in each river basin and for the country as a whole ; and

9. Preparation of groundwater maps giving information regarding depths to water-table, yield and quality of water in aquifers etc.

To cope with the stupendous tasks involved, the Survey has already laid a sound foundation. A Drilling Division for groundwater has been formed ; five regional geohydrological laboratories have been set up ; 205 permanent hydrograph stations are being established in the country this year. These stations will be utilized to observe the seasonal water levels all over the country. The coverage under systematic geohydrological studies is being expanded from year to year. So far only 85 geohydrologists could be deployed for this purpose. By October 1969 this number was raised to 130 geohydrologists and yet this is very low investment indeed, compared to the tasks and economic stakes involved.

The Survey's long term systematic groundwater studies have been reoriented basin-wise and from the current field season the studies will be

carried out continuously round the year. For this purpose investigating geohydrologists are being posted in their areas of operation. Field parties are being decentralised from the Divisional headquarters to twentyone groundwater district units with headquarters at various Regional and Circle headquarters of the Survey.

The systematic geohydrological studies in the twentyone groundwater districts have also the same identity of approach as laid down in the objectives of the International Hydrological Decade sponsored by the UNESCO. Therefore the Survey's programme for the International Hydrological Decade include the folowing programmes within the framework of the basin-wise geohydrological studies :—

1) Setting up of Hydrological Bench-mark Stations :

a. Ripu Reserved Forest : Sunphan sanctuáry : The Hel river Basin, Goalpara district, Assam.
b. Nambar Reserved Forest area : The Nambar river basin, Sibsagar district, Assam.
c. The Mohan river catchment areas, Gaya district, Bihar.
d. The Mahanadi Sanctuary : Mahanadi river basin : Darjeeling and Jalpaiguri district, West Bengal.

2) Intensive Hydrological Studies in Representative Basins :

a. The Jia Bharali river basin in Darrang district, Assam.
b. The Bhagalpur sedimentary embayment, Bhagalpur dist., Bihar.
c. The Burahbalang basin in the Balasore and Mayurbhanj district, Orissa.
d. Nadia-Murshidabad plain in Bhagirathi/Hooghly basin in the districts of Nadia and Murshidabad, West Bengal.
e. The Kaleghai river basin in the district of Midnapore, West Bengal.

3) Systematic Geohydrological Studies in Experimental Basins :

a. The Chandan river, basin, Bhagalpur dist., Bihar and
b. Damodar-Ajoy basin in western Burdwan dist., West Bengal.

In addition to the above, network permanent hydrograph stations being set up in 205 localities in India are a part of IHD programme.

During the I, II and III Plan periods 52, 42 and 59 items of systematic geohydrological investigations respectively have been carried out by the

Survey throughout the country. The studies conducted so far cover selected areas of the different groundwater basins. A large area still remains to be covered for a comprehensive understanding of the groundwater regime in different basins for dynamic programming of utilization of groundwater resources. Brief account of the work done in different basins is given below :

Brahmaputra basin : Systematic surveys have been conducted in the northern part of the Brahmaputra valley, north of the river in the Lakhimpur, Darrang, Kamrup and Goalpara districts of Assam and in the Coochbehar, Jalpaiguri and Darjeeling districts of West Bengal.

Groundwater occurs in these areas under confined as well as unconfined conditions. Exploratory drilling has reveoled the existence of an artesian belt largely in Brahmaputra "Tarai" extending from near the western boundary of Darrang district to adjoining Kamrup district, about 30 km. in length and 2 to 5 km. in width. The valley flat areas extending from Lakhimpur district in Assam to Jalpaiguri disirict, in West Bengal have groundwater both under water-table and confined conditione (deeper aquifers). The slope of the water table is generally in conformity with the topographic slope directed from the north to the south. In the Darrang district the gradient in the valley flat areas is of the order to 2 metres per kilometer. The groundwater consumption in the basin so far is insignificant. The heavy monsoon precipitation ensures large potentialities of groundwater recharge but due to lack of draft from the aquifer intake is uot considerable. There is thus a positive imbalance on surface run off. It may be pointed out that groundwater utilization in large scale would have a significant good effect in the decrement of surface run off and thus flood hazard, which is such an acute problem in this basin.

Deltaic plain of the Ganga and the east coastal plains of Orissa : The Bengal plain south of the Ganga (Padma) in the districts of Murshidabad Nadia, as well as northern parts of 24-Parganas, and Burdwan have groundwater storage in unconfined state and the productive aquifers lie within 200 metres of land surface. The general north to south and north-west to south-east directions of groundwater movement is discernible in this zone. This area is now under active stage of groundwater development for irrigational uses by heavy duty tubewells and detailed groundwater inventory is being made by the Survey. Trend surface analyses of water table in selected parts of Nadia-Murshidabad districts was made by Biswas (1967). In the lower deltaic plains of 24-Parganas, Howrah and Midnapore districts of West Bengal the groundwater storage is in relatively deeper aquifers (between 150—300 m.) and these aquifers are under confined condition. In the upland areas of the adjoining Bankura,

Midnapore, Burdwan, Birbhum and Western part of Murshidabad districts groundwater occurrence is both in confined and unconfined state and due to proximity of basement rocks boundary conditions are prevalent in several sectors resulting in hydrological features in distinction from the lower valley in the east and south.

The narrow coastal plains extending from the confluence of the Hooghly to Ganjam district in Orissa are charactersized by groundwater. in deep confined aquifers towards the coast. In the Midnapore-Orissa sector shallow groundwater bodies in alluvial and littoral sand beds occur under water table condition. The Ghyben-Herzberg principle was critically examined in course of systematic studies in the Midnapore coast (Goswami, 1968) and the equation was suitably modified in the light of data from field experiments. Wide variation of chemical characteristics in the groundwater is being studied.

East Coastal Plains of Andhra Pradesh and Tamil Nadu : The deltaic plains of the Godavari, the Krishna and older sedimentary deposits on the raised continental shelf of east coast continues through the Palar and Pennar basins to the southern end of Indian peninsula in the Kaveri basin. Groundwater occurs in older sediments in confined state while locally shallow groundwater bodies in water table condition also occur. The hydraulic parameters of the aquifers have been determined and sub-surface mapping of aquifers for large areas have been completed. Smaller sub-basins like the Palar, the Cooum, etc. have been studied in detail for groundwater resources assessment and determination of quantitative utilization potential. The artesian basin in Neyveli in South Arcot district has been explored exhaustively and a quantitative scheme of aquifer management prepared so that the industrial complex at Neyveli has been feasible. The regional pattern in geochemical evolution of the groundwater in different aquifers is being studied.

Ganga basin : The basin covers the alluvial tracts of eastern part of Haryana, entire Uttar Pradesh and Bihar. Studies conducted so far have revealed the occurrence of groundwater both in unconfined and confined conditions. The northern fringes of the basin have piedmont type deposits, known as *Bhabars* followed by *Tarai* zone in the south having alternating layers of very coarse sediments (pebbles and gravels to coarse sands) and finer clastics. The southern fringe of the basin is generally richer in finer clastics. In the central part alternating layers of sands and clays occur in abundance.

Within the *Terai* belt many well defined aquifers having enough pressure head to effect natural flow have been recorded. These

artesiant aquifers have their recharge zone in the *Bhabar* belt in the north.

In the central tract of the basin underlain by alternating layers of sands and clays, tubewells have generally been constructed within 150 metres below the land surface. The yield from the tubewells ranges generally from about 1,05,000 to 2,00,000 litres per hour. Deeper exploratory drilling down to 450 metres in the central part of the basin at Kanpur and Rae-Bareilly has revealed the existence of prolific aquifers below 250 metres depth capable of yielding about 1,30,000 litres per hour.

The southern and southwestern part of the basin is generally poor in aquifers e.g. Delhi, Agra and Mathura area.

Groundwater in the area is generally fresh and potable and suitable for domestic and irrigational purposes, except in the southwestern part of the basin where saline to brackish water occurs even in shallow zones at places.

Sindhu basin : This basin covers the alluvial tracts lying in the States of Jammu and Kashmir, Punjab, Haryana and Rajasthan.

Systematic studies reveal that the Kashmir valley fill is composed of Pleistocene Karewa formations overlain partly by the recent alluvium of Jhelum river. Groundwater occurs both under confined and unconfined conditions in the unconsolidated sediments. Flowing artesian conditions have been recorded in the lower reaches of alluvial fans in parts of the valley. The free flow from the tubewells tapping such artesian aquifers is around 22,500 litres per hour.

In the northern fringe of the basin occur *Kandi* and *Sirowal* conditions (equivalents of *Bhabar* and *Terai* of Ganga basin) where large groundwater resources have been indicated. Compared to the northern fringes the southern fringe of *Kandi* zone and *Sirowal* are more favourable for tubewell construction. Successful tubewells within a depth range of 90—150 metres yield upto 0.18 million litres per hour.

In the alluvial tracts of the basin groundwater occurs both under confined and unconfined conditions. In Punjab part of the basin, the tubewells generally constructed within 100 metres depth yield upto 0.18 million litres per hour. In Haryana area small localised areas have been found suitable for sinking of heavy duty and moderate duty tubewells. By and large the greater part of Haryana area is underlain by clayey formations and the quality of groundwater obtaining there is brackish to saline.

The greater part of the Sindhu Basin lying in Rajasthan is underlain by thin veneer of alluvium over consolidated to semi-consolidated rocks and thick aeolian deposits and is not suitable for groundwater development. Lathi group of sandstones (Jurassic age) in Jaisalmer district have proved to be the most promising water bearing formation.

Luni River basin : Studies in the area have revealed unfavourable geological and hydrological conditions for groundwater development by tubewells. The shallow zones having relatively low salinity are tapped by open wells. The most favourable tract for development of shallow zones lie southeast of Ahmedabad-Delhi line of the Western Railway.

Gujarat : Study of alluvial tract drained by the Sabarmati, Mahi, Dhadhar, Narmada and Tapi rivers and their tributaries show that groundwater occurs under confined as well as unconfined conditions. Near surface groundwater occurs in the depth zone of 9 to 24 metres. Sub-artesian water occurs between 24 and 61 metres depth and artesians water is found below 91 metres down to 366 metres below land surface. Quality of groundwater is uniformly good in the near surface and the sub-artesian zones and variable in the artesian zones. Yield of groundwater from all the three zones is moderate only.

The semi-consolidated rocks of Umia sandstones (Jurassic) in parts of Zalawad district and Bhuj sandstones (Jurassic) in Kutch as also sandstones of Katrol series (Jurassic) from water bearing horizons suitable for moderate to moderately heavy development.

West Coastal plains of Kerala and Mysore : Unlike the east coastal plains, the west coastal plains have very narrow width and discontinuity in the basins due to the projections of basement rocks in some sectors through the plains give rise to distinct geohydrological set up. The groundwater occurrence is usually in confined aquifers which have assorted granular materials. Wide variation in chemical characteristics also occur due to presence of conate water bodies at various depths. Systematic studies in these coastal plains are directed to detailed assessment of all factors mentioned above.

The Narmada-Tapti rift basins : These are inland alluvial basins occurring in the heart of central India. In the Narmada alluvial basin in Madhya Pradesh groundwater occurs both in confined and unconfined conditions. The slopes of water table as well as of piezometric surface are from the marjin to the centre of the basin. The disposition of the aquifers is responsible for these features. Generally the groundwater is potable with low concentrations of chloride and sulphate and bicarbonate

of calcium and sodium are predominent dissolved solids. Systematic studies for evolving long term groundwater management programme in this basin is in progress.

The Tapti basin is fringed by Deccan Trap lava flows and this characteristic of the basin province has reflected amply in the sedimentary deposits within the basin. There are few discontinuous aquifers of assorted granular materials which have limited possibilities of development. The main group of aquifers are under confined conditions and lie in faulted troughs in the central part of the basin. Groundwater in these basins is largely alkaline with predominence of calcium bicarbonate in them. Unlike the Narmada basin described above the distinct regional pattern of slope of piezometric surface is not discernible.

Chambal sub-basin : The Chambal is tributary to the Ganga and though the former has a fairly large catchment area, alluviation in its catchment has not been continuous. The pattern of basement topography in the Chambal catchment indicates a fair degree of peneplanation, so that the thickness of the alluvial deposits in the entire catchment is relatively small. However in many of the tributaries to the Chambal, such as, the Banas, the Koral, the Ban Ganga and the Kali Sindhu in Rajasthan have local troughs filled with relatively thicker alluvial deposits and such valley fill deposits have been found to contain fairly good storage of groundwater under water table condition. Some of these valley fill deposits have been assessed in considerable detail indicating storage, present stage of consumption, recharge and surface draft from the basin. Comprehensive assessment of the Chambal catchment as a whole is now in progress.

Minor alluvial basins : In addition to the large-scale basins described earlier, intensive studies for some smaller basins and sub-basins have been undertaken in various parts of the country. Amongst these mention may be made of the Kantli, the Dohan and Singhana basins in North-west Rajasthan, the Paonta and Bahl sub-basins in Yamuna catchment, Gomti basin in Tripura, the Purna basin in Maharashtra and the Vamsadhara basin in Andhra Pradesh. A comprehensive assessment of groundwater resources in these basins have been made establishing geohydrological control of occurrence, geochemical evolution and inventory of present consumption of groundwater.

Systematic studies of hard rock areas in India : The Peninsular shield of India and the Pre-Cambrian sediments forming extensive ancient platform deposits along the margins of the shield areas occupy nearly two thirds of the Indian sub-continent. The hard rocks in the Extra-Peninsular India lies in the Himalayan region. The groundwater studies in the

Himalayan region have so far been rather insignificant. However, fairly good coverage has been made in the peninsular area. Unlike the extensive storage rocks of the alluvial deposits and unconsolidated sedimentary rocks in the major river valleys and coastal plains described earlier, the occurrence of groundwater in the ancient crystalline rocks and consolidated sediments is controlled by factors specifically different. In these rocks groundwater movement is restricted in the upper most veneer of the weathered portions of the rocks which develop certain degree of permeability and in certain restricted channels within the unweathered rocks. These channels are joints and fissures, fault or shear zones and vasicles (only in the case of effusive rocks). Therefore, the concept of groundwater storage basins as applied to alluvial or unconsolidated rocks is not truly applicable in the case of such rocks. All the same, relatively poor availability of water resources in such terrain call for maximum rational utilisation of water resources available, and hence the urgency for systematic assessment of groundwater resources in the hard rock areas.

Based on physiographic and geomorphic characteristics and nature of rock types, systematic groundwater assessment in the hard rock areas are being taken up in seven distinct zones which have been delimited as separate groundwater districts. These are (1) Chhota Nagpur Plateau and Eastern Ghats of southeast India comprising parts of West Bengal, Bihar, Orissa, Madhya Pradesh and Andhra Pradesh, (2) east central highlands comprising parts of Maharashtra, Madhya Pradesh and Andhra Pradesh, (3) and (4) Plateau of Deccan Trap (North and South), (5) Krishna-Godavari catchment, (6) the Palar-Penner catchment and (7) the Southern plateau comprising parts of Mysore, Tamil Nadu and Kerala.

Studies in the hard rocks are directed towards understanding of the tectonic framework of regions mentioned above, the inherent physical features of rocks controlling weathering, depth and lateral extent of weathering and geochemical characteristics of groundwater.

Occurrence of fairly large storage of groundwater has been discovered in the Karstic limestones in selected parts of Rajasthan, Madhya Pradesh and Assam plateau. Similar groundwater occurrence has also been found in the Car-Nicobar island of the Andaman-Nicobar group which have been examined in details. Incidentally, it may be mentioned that hydrology of islands having primarily of semi-consolidated and consolidated rocks as obtaining in the Andaman Nicobar group has its own peculiarity and therefore systematic studies were also carried out in some of the islands of this group.

Acknowledgement

In addition to references cited in text the various unpublished- reports and scientific papers written by officers of the Geological Survey of India upto 1964 have been freely consulted in the preparation of this review paper. A comprehensive enumeration of the long list of such reports and papers would make a very long list and the same has been avoided in consideration of the space available.

GROUNDWATER IN HARD ROCKS IN INDIA

by

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The Nature of Hard Rocks

Hydrogeologically, hard rocks may be defined as those rocks which possess very little intergranular porosity. They are characterised by fracture porosity resulting from the presence of joints, fissures, solution channels and other such secondary openings. Hard rocks, then, would include all igneous and metamorphic rocks as well as highly compacted and indurated sedimentary formations. The distinctive features of groundwater occurrence in hard rocks have long been recognised. Generally, hard rocks yield not only limited supplies of water to wells but are also known to cause wide variability in the yields of wells even over short distances. Thus, prospecting for groundwater in hard rocks has long been intriguing to the hydrogeologist. Nevertheless, with accumulating knowledge and experience, this problem is becoming increasingly amenable to rational interpretation and solution. Much is yet to be achieved towards a fuller understanding of this complex subject.

Hydrology of Hard Rocks in the National Situation

In India, over 73 per cent of the area, totalling about 2.39 million sq. km., is occupied by hard rocks. A greater part of this area also coincides with areas of meagre and variable rainfall, frequently ravaged by drought. The well-being of the vast population inhabiting these tracts, and, in some crucial areas, their very survival, is dependant on a wise utilisation of the limited, available resources of groundwater. Towards such an utilisation, the Geological Survey of India has a major role to play.

The Role of the Geological Survey of India

Prior to Independence, the magnitude of groundwater investigations carried out by the Geological Survey of India was limited. Investigations were carried out to tackle specific areas and problems and the occurrence of groundwater in hard rocks was objectively dwelt upon in so far as it related to the problem on hand. After Independence, recognising the importance of groundwater as a natural resource, the scope of activities relating to it were increased and several large-scale reconnaissances were carried out throughout the country, aimed at a preliminary appraisal of the available resources. Some of these reconnaissances entirely related to hard rock areas while others related to areas partly covered by them. These re-

connaissances indicated that although the groundwater potential of hard rocks was rather limited, a careful delineation of the geologically favourable regions through systematic work would greatly aid in economic utilisation of the available resources for domestic, irrigation and industrial purposes. By the year 1960, with the setting up of the Regional Divisions of Groundwater a major step was taken in systematically studying the groundwater conditions obtaining in the hard-rock areas throughout the country. The work is gathering momentum and already several tens of thousands of square kilometres of area has been covered. In addition, numerous smaller investigations for specific water supplies have been carried out, all of which have yielded a wealth of valuable data on the groundwater regime in hard rocks. The systematic studies, have by far been the most important in a fundamental sense. These studies were aimed at studying, through detailed hydrological surveys the occurrence and movement of groundwater reservoir ; the hydraulic parameters of the reservoir as determined by pumping tests ; the study of the chemical quality of groundwater as related to its regimen and, in the light of these, to delineate areas where groundwater could be extracted for various beneficial purposes.

Purpose and Scope of Work

It can truly be stated that the subject of hard-rock hydrology is still in its infancy. India being one of largest countries in the world occupied by hard rocks, and the Geological Survey being one of the largest organisations of its kind in the world, studying the problem systematically, its knowledge and experience in this field is of national as well as international importance. At this juncture, therefore, a review of the activities of the department in this regard is not only desirable but also essential. The purpose of this review is to evaluate the present status of knowledge and to identify the various problems so that future work could be planned for maximum efficiency.

As would be seen from the list of references cited at the end, numerous workers have activiely been engaged throughout the country is studying the problem of groundwater in hard rocks. A bulk of their systematic work has been of fairly recent period and only a small part of it has, so far been published. A wealth of data, however, is contained in the unpublished reports of the department. An attempt has been made to include under the references, almost all the published works and selected unpublished reports by the officers of the Geological Survey of India relating to the subject.

Regime Characteristics

The regime of groundwater in hard rocks is dominantly a function of their physical and chemical make up. Hard rocks, by definition, possess very little intergranular porosity and can therefore hold a little of no

water of economic importance in their intergranular pore spaces. However, they do permit economic quantities of grounwater to accumulate and circulate in those openings that develop in them subsequent to their formation or emplacement. These openings are of two kinds ; the first of these are the joints, fissures and other such linear openings in the fresh rock which result due to the physical response of the parent rock to the various tectonic forces to which it had been subjected such as fault and shear planes, brecciated zones etc., while the second of these, which are more in the nature of intergranular porosity result due to the action the agents of weathering on the parent rock.

Thus, the groundwater reservoir, in which all the interconnected pore spaces are filled with water, is vertically divisible into two zones ; an upper zone of weathered material and a lower zone of interconnected fractures in the unweathered rock. Its top boundary is the water table, which lies mostly in the weathered zone and which becomes discontinuous where it lies in the fractured rock. The lower boundary of the groundwater reservoir is ill-defined and is represented by the base of the zone of interconnected fractures. Although the groundwater reservoir in hard rocks is generally shallow, its shape, depth and lateral extent are extremely variable, according to the lithology and structure of the rock. As the groundwater reservoir is directly dependent on rainfall for its recharge, the water table fluctuates in response to precipitation, allowing for sometime, layon on account of the infilttration time. The seasonal fluctuation in water levels may vary from less than a metre in valleys to more than ten metres under the water divides.

Control on Storage and Movement

Based on lithology and structure, hard rocks could be sub-divided into four main types, within each of which the groundwater reservoir is cntrolled by distinctive features. These types are :

1. The crystalline rocks including granites, gneisses, schists, amphibolites and associated intrusives.
2. The effusive lava flows e.g., basalts (Deccan Traps) Rhyolites etc.
3. The compact sedimentary formations, particularly of the Cuddapah and Vindhyan systems and, to a lesser extent, the Gondwana system and the compact sediments in the Himalyan Zone.
4. The carbonate rocks which are characterised by the development and of solution channels.

It is pertinent here to describe the distinctive features of these four sub-divisions.

The crystalline rocks

The crystalline rocks, comprising a variety of granites, genisses and schistose rocks occupy a very large area of the Deccan plateau, in the States of Kerala, Mysore, Tamil Nadu, Andhra Pradesh, Maharashtra, Madhya Pradesh, Gujarat, Rajasthan. Orissa, Bihar, Uttar Pradesh, and Assam as well as in the Extra-Peninsular region of Himalya. These rocks have undergone a very complex geomorphic evolution. In the Deccan they form elevated plateaux (the Mysore plateau, the Chota Nagpur plateau, the Bundelkhand plateau etc.), steep escarpments, (as along the Kerala coast), and the Himalayan region is characterised by high relief and deep gorges. Within each of these regional features could be deciphered the presence of several different levels of erosion and weathering. The plateau and the low-land areas are generally characterised by relatively flat to gently undulating topography with some amount of aggredation in the valleys. The escarpment areas as well as Himalayan crystalline tracts are usually characterised by strongly rolling to highly rugged terrains.

Crystalline rocks exhibit the development of joints and fractures to a widely variable extent. Commonly three types of joints could be observed ; the prominent foliation joint, the less developed transverse joint perpendicular to it and sub-horizontal sheet joints. In the more massive types, obliquely intersecting joints are common. The schistose varieties may locally exhibit openings developed due to schistosity and cleavage. The frequency and distribution of joints is seldom uniform. Joints, which may gape at the surface by a metre or more, tend to close rapidly with depth. Generally, below a depth of about 60 metres of ground level, the bed rock openings are so tightly closed as to be of little practical importance from the point of view of groundwater circulation.

Crystalline rocks, being rich in aluminuous silicates, are highly susceptible to disintegration and decomposition by the agents of weathering. The product of weathering is generally a clayey and gritty material. The depth of the zone of weathering is not only a function of the composition of the parent rock and the degree of weathering action, but also of the local topographiy, and climate which may or may not be conducive to the accumulation of the weathered material. Broadly, the thickness of the zone of weathering is more in the areas of low relief, as obtaining in the plateau or the lowlands and thinner in the areas of high relief, as in the escarpment tracts. The upper part of the weathered zone rarely exhibits any parental rock structures. This zone grades below into the partly weathered rock exhibiting parental rock structures, sometimes known as "saprolites". The saprolite, in turn passes often imperceptibly, below into the fresh, unaltered rock. The thickness of the weathered zone may vary from an edge to as much as 30 metres or more at places. More often than not, they tend to

thicken towards the valleys. The depth to bed rock below the zone of weathering is of significance in search for groundwater and therefore too quite often geophysical methods are deployed to determine precisely the depth to bed rock at any given place.

The effusive lava flows

The Deccan Traps (basaltic lava flows) occupy an area of about 500,000 square kilometres, in the central and western parts of Peninsular India, in the states of Andhra Pradesh, Mysore, Maharashtra, Madhya Pradesh and Gujarat. They represent vast accumulations of sub-horizontal to horizontal lava flows varying in composition from ultrabasic to acidic types, the most common variety being the basalt. They may be either massive and fine grained or highly vesicular and amygdular, the vesicles representing the vents through which the gases of the cooling lava had escaped and bubled up. The vesicles and amygdules are often filled with secondary minerals such as agate, quartz, chalcedony, zeolites and calcite, The lavas, which have originated due to huge fissure eruptions during the Cretaceous-Eocene period, sometimes include the Inter-Trappean formations, which occur sandwitched between successive lava flows. The Inter-Trappean beds include sedimentary rocks like sandstone, limestone and clays as well as effusive materials such as ash beds. In addition, thin beds of clayey, brick red material, known as "red bole" may also occasionally occur which are ancient lateritized or weathered surfaces developed during periodic intermission of the erruption of successive flows.

The different lava flows may vary in thickness from less than a metre to as much as 30 metres or more. Areally, they may extend from less than a few hectares to several tens or even hundreds of square kilometres. The Inter-Trappean beds are restricted in their distribution. Where developed, they occur as one or more beds at different levels, attaining a maximum thickness of seldom more than 15 metres individually.

The openings in the Deccan Traps include, joints, vesicles and cooling cracks and fault and shear planes. Inasmuch as the Deccan Traps consist of a succession of individual lava flows, each of which had been emplaced at different times, the characteristics of the secondary openings in each flow is governed by the conditions that had been prevalent at the time of its emplacement. In a single vertical section, therefore, it may be possible to notice several flows, each having its own distinctive features. The flows may be fine-grained, massive and poorly jointed or highly vescicular and well-jointed. When developed, vesicles and joints tend to concentrate towards the top and bottom of individual flows, with the core remaining more massive.

The most dominant topographic features of the Deccan Trap country are the flat-topped hills and the step like terraces. This is the result of the differential response of subhorizontal layers of varying strength to the agents of denudation. Local relief may vary from a few metres to several hundred metres.

Traps usually exhibit one or more sets of vertical joints and horizontal joints. In a few places, where conditions have been particularly favourable, columnar joints, consisting of the inter-section of more than three sets of vertical joints, are observed. As already mentioned, the depth and extent of these joints are controlled by the individual flows and as such, are fairly shallow, tending to diminish or disappear towards the middle of the flow.

The Deccan Traps usually weather with characteristic spheroidal exfoliation. The vesicular and amygdular flows are usually more susceptible to weathering than the non-vesicular types. The depth of weathering is again controlled by the properties of the individual flows and may vary from less than a metre to about 20 metres. In addition to the zones of weathering seen at the surface at present, buried zones of weathering representing ancient cycles of denudation, subsequently buried by the younger flows may also exist in some areas.

The effusive basalts of Rajmahal hills in Bihar, the Shillong plateau, Assam and the Panjal range of Kashmir also show similar features.

The compact sedimentary formations

Highly compact sedimentary formations, comprising a variety of quartzites, sandstones, shales and limestones (unaffected by the solvent action of water), belonging mostly to the Cuddapah and Vindhyan systems and, to a lesser extent, to the Gondwana system, occupy vast areas of the country. The more important and extensive of these tracts are the Cuddapah and Pakahl basins in Andhra Pradesh, the Kaladgi and Bhima basins of Mysore, Maharashtra States ; the Vindhyan basin of Madhya Pradesh, Uttar Pradesh and Rajasthan and the Chattisgarh basin of Madhya Pradesh and Orissa States. There are, however, compact sedimentaries in the orogenic belt of the Himalaya which are late Mesozoic to Tertiary in age, in addition to those mentioned earlier. Relative to the attention bestowed on the systematic groundwater studies in the crystalline rocks and the Deccan Traps, the quantum of data available of the groundwater conditions on the aforesaid formations are limited.

The geomorphology of these basins is quite complex, giving rise to a variety of land forms characterised by numerous surfaces of erosion, systems of hills and valleys. Due to their bedded nature and the alternation of layers of varying competance, the types of joint systems that develop in these formations is difficult to generalise. The rocks may vary from

unjointed, massive types to highly jointed ones. There is reason to believe that some areas of intensive structural and tectonic deformation, the joints and other laminar fracture planes may persist down to great depths, at least a few hundred metres below ground level.

Being themselves products of weathering and transport, sedimentary rocks are usually much less susceptible to weathering than the igneous and metamorphic rocks. They are more prone to physical disintegration than chemical alteration. As such, the depth of weathering in these rocks is usually relatively small.

The Carbonate rocks

Due to the slow but continuous solution of calcium carbonte in water under physico-chemical conditions normally obtaining under in atmospheric or near atmospheric conditions, through the geologic ages, the carbonate rocks often develop intricate solution channels within the regime of groundwater in certain areas. In such, Karstic tracts, large openings in the limestones are created by the enlargements of fractures and fissures by the solvent action of groundwater. The nature and distribution of these solution channels to a great measure control the geomorphic evolution of the terrain.

In India, carbonate rocks comprising limestones and dolomites are known in the Archaeans, in the Cuddapah and the Vindhyan formations and their equivalents, in the Mesozoics and Tertiaries. They occur scattered throughout the country in almost all the States of the Union. However, the presence of large solutions channels in them has been reported from very few places, as in some areas occupied by the Kurnool rocks in Andhra Pradesh, in the Jaisalmer area of Rajasthan, in parts of Mirzapur district in Uttar Pradesh in the Kopili limestone of Assam plateau and in some islands of the Andaman Nicobar group and the Laccadive group. Even in these areas, the surface expression of these solution channels is very poor except in the Kopili limestone of Assam. Very little systematic work has been carried out on the regime of groundwater in the various carbonate-rock tracts of the country where solution channels exist. Recent work, employing tracer techniques carried out in the Kopili project reservoir area, indicated the existence of large solution channels and caverns right from the land surface to depths of 120 metres and these indicate a very rapid movement of groundwater in these channels.

Control on Groundwater Storage

The storage of groundwater in hard rocks is controlled by the zone of weathering and the interconnected fractures in the bed rock. In the case of the crystalline igneous and metamorphic rocks as well as the effusive rocks the mantle of weathering appears to possess a greater capacity to store and yield water than the fracture zone. In the case of the compacted sedi-

mentary formations, which are less susceptible to weathering and more susceptible to fracturing, and in the case of carbonate rocks with well developed solution channels, the control of fracture porosity on groundwater storage is apparently more. Very little data is presently available to even approximate quantitatively, the amount of water these different hard rocks can store and yield for development. A lack of these important parameters is partly to be attributed to their inherent difficulties in their determination using field methods. Most known existing methods of groundwater hydraulics, applicable to soft rocks, are inapplicable in the case of hard rocks, the clayey, non-homogeneous nature of the weathered zone, the erratic distribution of fracture porosity and the effect of well storage on dischange.

Control on Groundwater Movement

The groundwater reservoir in the hard rocks being dominantly shallow in nature, its movement is to a very large extent governed by topography. The flow pattern thus governed is modified by the presence of local geological features like faults, shear zones, dykes and quartz veins ; where favourably situated, dykes and quartz veins act as barriers to groundwater movement while faults and shear zones may act either at as conduits or barriers depending on whether or not they are annealed.

Within the zone of weathering, the natural movement of groundwater is relatively shallow, almost being restricted to the zone underlying the gross topographic slope, extending from the surface divide to the base of the valley. Groundwater, in this zone occurs generally under unconfined conditions. It continuously moves towards the valleys from the superjacent interstream areas. All the streams are invariably effluent. The water-table is a subdued replica of the topography and the depth to water level in wells tends to be shallowest in valleys than on the high grounds.

The movement of groundwater in the zones of fracture is ultimately related to their interconnection. Where the zone of weathering is conspicuous, it directly recharges the fractured zone and controls the movement of groundwater in it. Locally, within the zone of fracturing, groundwater may be under confined conditions.

The flow of groundwater in the cavernous limestones differs considerably from that in the other three types of hard rocks in whose case, the flow of groundwater seldom crosses a water divide. However, in the case of cavernous limestones, the nature of the solution channels control the movement of groundwater more than the local topography. Often, large quantities of groundwater may leak from-one groundwater basin to another, if limestones with well developed solution channels are present.

Springs

Springs and seepages, which have a definite place in the regime of groundwater occur scattered throughout the country in hard rocks. Shallow springs, controlled by the intersection of the water table with the land surface or by the favourable distribution of joint systems on hill slopes are quite common. In the Deccan Traps, springs may also result due to the horizontal migration of groundwater in the plateau areas and emerging on the terraced slopes. Springs, controlled by joints and of conspicuous discharge (as for example, the very spring which supports the Jhelum stream flow) may occur in limestone areas.

Springs of deeper origin, usually warm and selectively enriched in minerals are known to occur in several parts of the hard rock areas, of the country. Tectonically, these springs could be grouped as follows :

a) Springs located in the stable Peninsular shield, unaffected by post Paleozoic movements, such as those in Kerala, Mysore, Tamil Nadu and western Andhra Pradesh—Temperature : 28 to 32° C.

b) springs associated with areas affected by Mesozoic volcanicity or post Gondwana movements, such as those of the Cuddapah basin in coastal Andhra Pradesh, Orissa, Chota-Nagpur plateau, Assam, Madhya Pradesh, Rajasthan and Maharashtra—Temperature : 35 to 72° C.

and c) springs in the post Mesozoic mobile belt of orogeny, such as those of the Himalayan region in Ladakh, Punjab, Uttar Pradesh and Nepal. Temperature : 50 to 102° C.

Chemically, water from most of the springs is low in dissolved mineral constituents, usually less than 500 ppm. and rarely more than 1000 ppm, with bicarbonate, chloride and sulphate as the dominant ions. Everywhere these springs are predisposed by faults, fissures and joints. Rainfall appears to be the chief source of water of these springs, circulating deeply along the fractures. However, in some cases, as in the case of the West Coast springs of Maharashtra, which usually contain 2000 to 3000 ppm. of total solids and rich in chlorides, the possibility of a magmatic origin for the water cannot be ruled out.

Quality of Groundwater

The chemical quality of groundwater in various types of hard rocks is variable, being controlled by the bulk chemistry of the parent rock, the existing soils and the locale of sample in the groundwater flow system. Over large parts of the hard areas of the country, wells normally yield waters with less than 1000 to 1500 parts per million of total dissolved solids, being more or less suitable for domestic, irrigation and industrial purposes.

However, there are certain tracts where the groundwater may contain 2000 to 10,000 parts per million or more of dissolved solids, rendering the water unfit for domestic, irrigation or industrial purposes.

In general, groundwater from areas occupied by granites, gneisses, schists, sandstones and quartz it is usually slightly acidic, relativly soft and low in dissolved mineral content. Groundwater from areas occupied by basic rocks such as basalts, amphibolites and limestones tends to be alkaline, rather hard and high in disolved minerals.

In the hard rock areas, poor quality waters are chiefly restricted to the deep valley tracts where black soils have accumulated to a large thickness. A typical example may be quoted from Bijapur district of Mysore State, where much of the Dhoe river basin has been affected by such a hazard. This river, whose base flow is sustained by the groundwater reservoir, shows very high content of dissolved mineral matter, containing over 3000 parts per million of dissolved salts.

In the more chronically affected areas, fresh water floats on brackish water as a thin layer, immediately after the monsoons. Taking advantage of this, shallow wells are judiciously dug, only to tap the upper, fresh water zone. As the water table falls, however, the quality gradually deteriorates, causing acute scarcity for potable water in the summer months.

The alkaline tracts, which occupy a lesser area than the black soils, are the second chief cause of water quality hazard in hard rock areas. These are generally restricted to zones of natural groundwater discharge in arid lands, where parent rocks rich in alkalies may exist. The groundwater in these tracts is highly alkaline with a dominance of Sodium and Potassium ions over those of Calcium and Magnesium. These alkaline waters are often unfit for cultivation save a few tolerant crops.

A third type of quality hazard is that of fluorosis in some restricted granitic and gneissic tracts. Fluorosis is a malady affecting the joints and teeth of human beings and cattle and is thought to result from the presence of fluorine in drinking waters, in excess of 2 parts per million. The prevalence of fluorosis has been reported from several parts of Andhra Pradesh, where some well waters contain more than 5 parts per million of fluorine. Although the bulk chemistry of the country must be the source of this fluorine, the factors affecting its distribution and concentration in groundwaters is not yet fully understood.

Apart from the natural causes referred to above, the effect of pollution on groundwater in hard rocks is worth mentioning. Throughout the hard rock areas, groundwater in wells situated in the centre of the inhabited parts of villages usually yield poor quality waters while wells situated outside the villages may yield potable waters. The effect of pollution in these

cases on the quality of groundwater would be quite apparent. In addition, many potential valleys adjacent to towns and cities are also affected to various degrees because of sewerage and waste water disposal.

Status of Groundwater Development

Presently, groundwater is being developed over much of the hard rock areas for domestic, irrigational and industrial purposes. The distribution of these areas of development is, however, heterogeneous. Thus, over vast areas covered by the black cotton soil, where groundwater is of markedly poor quality, its development is practically negligible. These are the typical tracts, where cultivation is carried out in the *rabi* season by the "dry-farming" methods taking advantage of the soil moisture available. Again, in areas of high relief, where fresh rock occurs at shallow depths and the soil cover is infertile and thin, groundwater is little developed for small domestic supplies only. Over the rest of the area, groundwater is being increasingly developed by means of dug wells, dug-cum-bored wells and bored wells. The most popular of these is the dug well, supplemented in some cases by one or more bores at the bottom to ensure sustained water supply. Bored wells are relatively less in number than the other two types.

Depending on the purpose for which they cater, dug wells may range in dimensions from about a metre to as much as 20 m. across. They may be square, oblong or circular in cross section and range in depth from less than 5 to 30 metres or more, depending on the local water table conditions and its fluctuation. The dug wells may be lined with porous bricks, rock or laterite, the lining rarely extending below the zone of complete weathering. Wells in partially weathered rocks and jointed rocks are usually left unlined. The yield of wells may very from less than 22.5 cu. m. (5000 gallons) to as much as 450 cu.m. (100,000 gallons) of water per day in the extreme cases. More commonly, the yield ranges from 90 to 135 cu.m. (20,000 to 30,000 gallons) per day, in the case of favourably located wells of moderate dimensions. Depending on the local soil conditions, crops, and the availability of surface water for conjunctive use, these wells may irrigate from less than a hectare to about 10 hectares. Besides, many towns in hard rock areas receive water supply from dug wells or dug-cum-bored wells.

Bored wells, ranging in diameter from 10 to 20 cms. (4 to 8 inches) are used in restricted areas for groundwater development, principally for domestic and industrial purposes. Some attempts are being made to utilise them for irrigation purposes as well, in preference to open wells, over which it has a few advantages.

Bored wells seldom exceed a depth of about 70 metres in hard rocks, although wells as deep as 150 metres have been attempted in some areas. Experience has shown that below a depth of about 70 metres of ground level, the yield of wells is not significantly augmented. Drilling machines of the coring type, are usually employed for drilling bored wells. Percussion methods are employed to a lesser extent. More recently, down-the-hole hammer rigs, as well as air-driven drills capable of rapid drilling in hard rocks, are being employed in some parts. The bored wells may be either partly lined or unlined, depending on the ablility of the formation to retain the well wall. The yields of these wells are widely variable, from less 0.5 cu.m. (100 gallons) to seldom more than 13.5 cu.m. (3000 gallons) per hour. Commonly, a well with a sustained yield of about 4.5 cu.m. (1000 gallons) is considered a good success. The drawdown in the bored wells may range from less than 3 metres to over 30 metres depending upon the groundwater reservoir parameters.

The most common methods of lifting groundwater for relatively large requirements in the case of dug wells and dug-cum-bored are the bullock driven piccotah or mote, the bullock-drawn persian wheel and the centrifugal pumps. Due to the limited permeability characteristics of the groundwater reservoir in hard rocks the inflow into open wells is usually low and much of the water pumped out comes immediately from well storage, so that, within a few hours of pumping, the well may either completely dry up or the pumping level may go below the suction level of the pump. Recovery to static level, after the pump is shut down, may even take a few days. Usually, however, within a period of 24 hours, the recovery is of the order of a metre to a few metres.

In the case of bored wells, water may be lifted by hand pump, compressed air, turbine pump or submerssible pump. In the State of Mysore, where numerous town water supplies are based on one or more bored wells, the compressed air method is popular. Turbine pumps and submerssible pumps are usually favoured by industrial users. One of the disadvantages of the airlift method is that, at least in some areas, the air-water inter-action decreases the solubility of dissolved salts, particularly calcium carbonate, which is precipitated to form thick encrustations, often choking the well assembly.

Potentialities for Development

Though the groundwater resources of hard rocks are limited the present state of knowledge suggests that there is considerable potential yet to be developed. At present, there are areas where the existing number of wells could be increased. There are other areas where groundwater is yet

to be developed partly due to a lack of knowledge of the available potential and partly due to a lack of suitable facilities for its extraction. Thirdly, the existing potential could be greatly augmented by taking suitable measures of increasing recharge to the groundwater reservoir by improving the the methods of groundwater extraction and by devising measures of gouun-water management, giving due consideration to surface water-groundwater relationships.

Methods and Techniques

Hitherto, detailed well inventory, in conjunction with geological mapping has been the basis of much hydrogeological work in hard rock areas. Attempts have been made to demarcate the outcrop areas, particularly in gneissic and granitic terrains and delineate the favourable vesicular basaltic units in the Deccan Trap areas. Based on these and a study of the chemical quality of groundwater from selected wells, areas have been deciphered where further groundwater development could take place

In addition, pumping tests have been conducted on existing open wells and bored wells to study the yield characteristics and deciding upon the type and dimensions of wells suitable for various needs.

In areas of particular interest, geophysical methods have been employed to aid in groundwater prospecting. These methods consisting principally of electrical resistivity soundings and depth probes and, to a lesser extent, on seismic refraction surveys, have aided in deciphering the depth to bed rock and isolating zones of deep weathering. To a limited extent, test drilling has been resorted to in some places to confirm the rseults of geophysical exploration.

Tracer techniques, using radioactive tracers have been employed in some areas to study the movement of groundwater, as for example in the Kopili dam area of Assam.

Problems and Prospects

The work so far carried out in hard rocks has indicated that there exist several problems that need to be tackled. It is pertinent at this juncture to identify these broad problems and recognise the means to solve them.

The foremost problem is that of groundwater prospecting, both at a regional and at a local level. The area to be covered is very large and the technical man power available, limited. There is an urgent need to assign priorities for further intensive hydrogeological studies in specific regions, based on their promise of groundwater potential. This would envisage

a division, at a regional level, of subdividing the different hard rock areas of the country on the basis of geomorphology and tectonics, preferably on a scale of about 1 : 250,000. Study of air photo mosaics wherever available or feasible or the use of quarter-inch topo sheets of the Survey of India, may be ideal for this purpose. Such a subdivision would help identify, besides helping in assigning priorities for detailed work, the existence of various levels of erosion and thus, possibly, the zones where groundwater may find its way by leakage from one reservoir to another at a lower elevation; the regions of active erosion where the weathered mantle is being continuously removed and the regions of strong structural control where detailed prospecting may reveal the existence of hitherto undeveloped bodies of groundwater.

Based on studies on the above lines further intensive investigations could be carried out, preferably on aerial photographs of the conventional 1 : 30,000 scale or the topographic sheets of 1 : 50,000 scale. This work, by a careful study of the distribution of rock outcrops, topography, drainge, soil characteristics and other features and suitably followed by field checks, would help in the rapid delineation of suitable areas for groundwater development. This would serve the immediate purpose of the various developmental agencies at the state and district level.

Perhaps the most intriguing problem of groundwater occurrence in hard rocks is the pin-pointing of well sites. Although siting wells in areas delineated by the methods of regional prospecting would minimise chances of failure there still remains some possibility of failure or low yield. This problem is intimately related to identifying the sites where the zone of weathering is relatively deep or where fracture porosity is maximal. To identify these locales, the best possible way appears to be that of carrying out careful studies of the mechanism of weathering as well as patterns of drainage in relation to the geomorphic processes and features. A careful study of the weathering profile in typical geomorphic and lithological units as well as exploratory drilling in carefully selected areas of structural control may aid in this. Drilling in structurally deformed areas, particularly in the sedimentary basins of the Cuddapah and Vindhyan systems and possibly also in some of the ancient schistose belts, may indicate zones where groundwater may circulate down to relatively greater depths through interconnected, deep-seated fractures.

In the Deccan Traps, if the massive units separating the vescicular units contain some major fractures, then, such fractures may transmit water from the upper to the lower unit by leakage. Should such conditions exist, it may be possible to tap the lower horizons by means of bored wells, which may yield water under high pressure head or artesian conditions.

Considering the vast areas occupied by limestones in the country, the reported occurences of Karstic conditions are relatively few. It seems possible that such areas have not hitherto been discovered in greater numbers due to a lack of surface expression of the solution channels. An intensive search to discover areas of cavernous limestone, therefore, seems worthwhile considering their role as good channels for groundwater movement and storage. A careful study of the geomorphology of limestone areas, with particular emphasis on past climatological evaluation may throw significant light on probable Karstic provinces.

The quality of groundwater is a major hazard, specially in areas of black cotton soil. Detailed studies on the variation of chemical quality within the black soils, to decipher whether any vertical or horizontal zoning exists in water quality may help in pointing out better ways of utilising groundwater in these tracts. Similar geochemical studies may also be carried out in areas affected by alkalinity and fluorine content of groundwater.

Almost all the problems of groundwater occurrence and quality are intimately related to the movement of groundwater within the groundwater reservoir. Therefore a study of the regional groundwater movement is of paramount importance. In recent times the study of grounwater flow systems, through studying the distribution of fluid potential within the groundwater reservoir are becoming increasingly popular. Such studies, to start with, could be initiated along selected traverses in typical areas. They are likely to throw considerable light on the exact nature of groundwater movement within the groundwater reservoir in hard rocks.

At present we have very little data on the hydraulic parameters of materials constituting the groundwater reservoir in hard rock areas. These characteristics are of vital importance in the estimation of the storage available, the computation of the optimum spacing between wells and in the preparation of a groundwater budget. Hitherto, a greater part of our knowledge on hard rock hydrology has been basically qualitative in nature. There is an imperative need for quantitative evaluation of the various factors.

The chief difficulty in tackling the hydraulics of the groundwater reservoir in hard rocks has been their poor permeability and storage, the heterogenity in the distribution of the pore spaces and the peculiar shape and internal structure of the groundwater reservoir. Field tests on open wells and bored wells have hitherto been of help only in giving a broad idea of the yields of wells but not the parameters of the groundwater reservoir. Intensive work in the field, using better devised pumping tests

and tracer techniques and in the laboratory, studying the hydraulic properties of carefully collected samples in the laboratory should be of considerable help in this regard.

By far the most popular means of groundwater development in hard rock areas in India has been the dug well and to a lesser extent, the dug-cum-bored well. However, bored wells are now becoming popular, at least in some areas. An objective evaluation of the relative advantages has been rather difficult because the difficulties inherent in understanding the hydraulics of the open wells piercing a poorly permeable formation.

The ultimate problem which the science of hydrogeology seeks to tackle is that of judicious groundwater management. In hard rock areas, the groundwater reservoir being shallow and immediately related to rainfall, much of the recharge takes place *in situ*, within the given region. Therefore, all the groundwater that is developed within the region comes almost entirely from reacharge within itself.

In order that there may be balance between recharge and discharge within a given region, it follows that there must be a balance between the areas of recharge left free of development and the areas where groundwater is to be extracted in relatively large quantities, particularly for irrigational purposes. Alternative use of the recharge areas for pasture, contourbunding and other purpose would augment recharge to the groundwater reservoir, increasing thereby, its potential.

The various problems could be systematically tackled with suitable facilities, techniques, equipment and man power. In the recent past, several far-reaching steps have been taken up by the Geological Survey of India towards achieving these ends. For example, the formation of different groundwater district units would facilitate the immediate division of the various hard rock tracts of the country into various hydrogeological units on convenient scales.

The Geological Survey of India is hopeful that the various problems would be effectively solved and that the department would fulfil its role in the judicious utilisation of the groundwater resources of hard rock areas.

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PROBLEMS OF GROUNDWATER DEVELOPMENT IN INDIA

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Introduction

Groundwater is a factor in soil formation. It may be the controlling factor in petroleum accumulation. It is also a critical factor in many engineering problems particularly in regard to soil mechanics. It represents the largest source of fresh water available on the earth. Total amount of water stored in the aquifers below ground greatly exceeds the total volume of water in lakes, streams, and reservoirs, throughout the world.

Advantages of groundwater development greatly outweigh the surface water development for the following reasons :

i) unlike surface reservoirs, groundwater reservoirs have been naturally created,

ii) less cost of development and distribution system compared to surface water schemes,

iii) total storage valume of underground reservoirs are considerably greater than surface reservoirs and is available for use at the point of requirement without causing excessive depletion,

iv) remarkably uniform temperature of groundwater is a decided advantage for industrial and related water supplies,

v) immediate response of surface reservoirs to lean rainfall,

vi) their relative freedom from pollution.

In recent years, with near optimum development of our surface water resources and lesser cost involved, the trend for placing greater reliance on groundwater development is discernible.

Basic Requisites for Groundwater Development

Development of groundwater resources needs thinking in terms of groundwater basin as a unit. For perennial maintainance of the resource, a hydrologic equilibrium should exist between all the waters entering and leaving the basin. Evaluation of the equation of hydrologic equilibrium presupposes that all the factors in the equation can be measured. In practice, if all but one can be measured, which can be solved for as an unknown, then the equation can be handled on a quantitative basis. In working with a large groundwater basin, long periods of time and adequate records are necessary in order to obtain the data required. It is necessary for example, to have measures of total stream flow in and out of the area, total imports and exports of water, precipitation, consumptive use, changes in surface water storage, changes in groundwater storage ,and evaluations of subsurface inflow and outflow. In practice, careful evaluation of this equation in a basin may often require several years of collection and analyses of basic data.

A variety of factors control the feasibility of any groundwater development programme. The principal one being its physical feasibility i. e., whether groundwater is available, can it flow through the aquifers existing in the area as also is there any possibility of recharging the groundwater body ? Next in importance comes the economic feasibility, which involves cost analysis for investigating and exploring the hydrogeological conditions and engineering costs for its development and management. Of no less importance is the factor of financial feasibility. Money must be available from some source whether State, private or social bodies. Social feasibility cannot be lost sight of. The local populace that would ultimately utilise the groundwater supply must provide active support and co-operation necessary for its development. And lastly, the political feasibility i. e., clearance must be available from private or public bodies whosoever are the legal owners of the basin requiring development.

Hydrogeological Set-up and Development Peculiarities

Amongst the various factors enumerated above, by far the most important one is the physical feasibility. The various factors that control the physical feasibility i. e., availability of groundwater, are hydrogeological set-up, geomorphic features, metereological conditions, and the chemical quality. From view point of similarity in hydrogeological set-up and developmental problems the Indian mainland can be divided into three major units and several sub-units as detailed below.

A. Areas Underlain By Unconsolidated Sediments

i) Sindhu-Ganga-Brahmaputra Alluvium :-

a) *Bhabar* and *Terai* Belts
b) The Central Tract
c) Fringe Belt Adjoining the Shield.

ii) Coastal Alluvia

a) Eastern Coast
b) Western Coast
c) Gujarat Alluvial Flat

iii) Ganga Delta

iv) Inter-Montane Valleys :-

a) Kashmir Valley
b) Doon, Paonta, Nurpur, Bahl Valleys

v) Valley-fill Areas

vi) Intra-Cratonic Basins
Narmada-Tapi-Purna Basins

vii) Aeolian Sand Tracts

B. Areas Underlain By Semi-Consolidated Sediments.

i) Paleo-Mezozoic-Tertiaries of Western Rajasthan
ii) Coastal Areas
iii) Gondwana Basins.

C. Areas Underlain By Hard Rocks

Of the total surface area of the country i. e., 3.2 million sq. km. about 2.388 million sq. km. are occupied or underlain at very shallow depths by compact rocks, of the remainder, consolidated Paleo-Mesozoic sedimentary rocks occupy some 0.061 million sq. km. semi-consolidated to consolidated Tertiary sediments are exposed over an area of 0.172, million sq. km. while unconsolidated Quaternary sediments mantle about 0.579 million sq. kms.

Salient hydrogeological features including availability of groundwater and attending problems for its development are briefly discussed in the subsequent paragraphs.

A. *Areas Underlain by Unconsolidated Sediments*

These include the alluvial tracts of the Sindhu-Ganga-Brahmaputra river systems, the coastal alluvial tracts, inlnad river basins, intermontane valleys and tracts covered by wind blown sands.

Singhu-Ganga-Brahmaputra Alluvial Tract : This tract occupies the depressed zone between the mountaneous region of the north and the Peninsular region of the south extending from Jammu in the west to Assam in the east. This depression is considered to be an orogenic zone of downwarps which is in continuity with the earlier Siwalik orogenic trough of late Miocene to early Pleistocene age. Recent studies have revealed that the thickness of the alluvium in the central part of the tract (Bihar) is about 1830 m. and in the deltaic region near Calcutta, it is of the order of 2000m. This alluvium is made up of the sediments brought by Sindhu, Ganga and Brahmaputra river systems. Variation in sedimentation in geological past and consequent changes introduced in the drainage patterns of the Himalayan rivers have brought about in their wake an intricate pattern in the disposition of the aquifer horizons throughout the length and breadth of this tract. The nature of sedimentation and pattern of distribution of the aquifer system plays a dominant role in the occurrence, storage, recharge, transmission and consequently in the development of the groundwater resources.

(a) *Bhabar and Terai Belts* : The northern belt of this alluvial tract, girdling the Himalayan foothills, is characterised by coarse detrital materials principally boulder-gravel in the nature of high level coalescing talus fans froming the piedmont terrain usually referred to as *Bhabar* or *Kandi*. This is followed immediately to the south by the *Terai* or the *Sirowal* belt of stratified alternating extensive bands of dominantly coarse sediments and clay. The southern belt of this tract fringing the peninsular shield is distinguished by the prevalence of dominantly finer sediments. The central part lying between these belts shows variation in sediments lying within these limits. These sedimentological features have their imprint on the groundwater development problems.

Geohydrological continuity between *Bhabar* and the confined aquifers of the 'Terai' belt, the vast intake zone spreading along the northern parts where prolific recharge is effected by rainfall and hilly streams, the highly porous and permeable nature of formations would ensure large supplies of groundwater from the *Terai* belt for agricultural and industrial use. It has been established that southern parts of *Bhabar* belt and the entire *Terai* belt have huge groundwater reserves. Large scale groundwater development programmes for the *Bhabar* and *Terai* belts will be distinctly different in as much

as the *Bhabar* will pose problems of drilling through thick boulder beds and involve very high water lifts from deep water table. In the *Terai* belt the problems that would be of paramount importance will be to successfully control great hydrostatic pressures encountered in drilling through each artesian aquifer. In the *Terai* belt groundwater development and its conservation will have to run concurrently to prevent the uninterrupted free flow from the tubewells. The northern part of *Bhabar* zone, underlain by highly porous and permeable materials, appear to be ideally suited for introducing waterspreading as an effective flood control measure. This will also increase the potential of the aquifers underneath through recharge shifting thereby the southern boundary of the 'artesian belt' further south and improving the agro-economics of the area.

(b) *Central Tract :* This tract merges imperceptibly with *Terai* belt in the north and with the alluvial belt adjoining the peninsular shield in the south. It has three major basins—in the west, covering greater part of Punjab, lies the Sindhu basin, the Central part, covering by and large greater parts of U. P., Bihar and Bengal, is occupied by Ganga basin and in the east occupying a considerable portion of Assam is the Brahmaputra basin.

This alluvial tract has an immense underground reservoir of fresh water, one of the largest in the world. It also supports our richest and widest agricultural lands, and if given its due attention it is destined to become the greatest asset in our national economy.

Within these three major basins there are a number of subdrainage basins which are drained by tributaries of Sindhu, Ganga and Brahmaputra. In Sindhu and Ganga basins occur series of almost, parallel valleys and watersheds. In the former, these valleys and watersheds run approximately ENE-WSW while in greater part of the Ganga basin, these trend NNW-SSE. Migration of the tributaries draining these valleys have resulted in conspicuous back-swamp and meander belt deposits. These sedimentological features play a dominant role in the hydrodynamics of the region.

Results of deep drilling carried out in recent years at Kanpur, Raibareilly and parts of eastern U. P. and deltaic region of West Bengal, show the presence of prolific aquifers which are likely to have wide areal extensions, generally below 250 metres only.

Greater part of these basins, however, are underlain by several interconnected extensive aquifers within the depth range of 200 metres. Groundwater exploitation in these basins initiated during early thirties, have been progressing rather indiscriminately with an ever increasing pace independent of aquifer potential or in utter disregard to the operational

yield of the ground water basin. If the trend continues, it may lead to areas of localised heavy withdrawals, which may cause land subsidence and related problems.

Incidentally, these basins have a well developed surface irrigation system, some of these are in existence for over a century. Such canal systems, have been responsible for the creation of water-logged conditions and attendant land salinisation problems. Extent of such water logged and saline areas is progressively on the increase.

This fact has to be taken into consideration while formulating basinwise groundwater development programme for this tract.

In the Brahmaputra basin the huge thickness of alluvial deposits are mainly restricted within the flood plains of Brahmaputra river system; sand and gravel beds within these deposits form the principal aquifers. Groundwater in them often occur under confined conditions and in favourable topographical locations flowing conditions have been encountered.

Studies made so far indicate that potentialities of the aquifers in the Brahmaputra basin are of a very high order. The alluvial plains lying to the north of Brahmaputra river, in particular, will support large scale development of groundwater.

In contrast to other parts the problem in this area is more of flood control than groundwater development. Integrated use of surface and groundwater potentials is imperative for water resources development.

(c) *Fringe Belt Adjoing the Shield :* In the belt immediately fringing the peninsular shiled the thickness of the sediments generally does not exceed 150 metres. The sediments are dominantly clayey containing lenticular beds of granular material of varying areal extent. *Kankar* beds occurring at various depth ranges normally prove to be potential aquifers. In the western part of this belt, west of Bah covering parts of Agra and Mathura districts in U. P., Delhi State, southern part of Rohtak, Gurgaon and Mahendragarh districts in Haryana, the subsurface formation water is generally saline. Zones containing fresh water occasionally occur either as phreatic water generally not exceeding depth of 20 metres below ground level or as alaternating beds with saline horizons and having restricted areal extend. The deeper zones as a rule contain highly mineralised water. In view of the lenticularity, the aquifers operate under boundary conditions.

Groundwater development problems in this terrain are chiefly that of quality rather than the quantity, which involve precise delineation of the fresh water zones, judicious grouping of aquifers having varying chemical quality of water to yield water of an acceptable quality, and effecting

sealing-off of the saline zones Upcoming of the saline water into the wells have also to be prevented either by careful regulation of the groundwater draft or through a system of coupled wells pumping simultaneously in the freshwater and the saline water zones respectively. The latter techniques of exploiting the fresh water lenses are in vogue in the Soviet Union and West Pakistan. In view of the finer nature of the aquifer materials, utilisation of the porous ceramic filter (PCF) is considered to be most advantageous. These filters possess the special quality of complete chemical inertness which renders them suitable for application in waters of any chemical quality besides helping in reducing the period of well development.

East of Bah, extending upto the Rajmahal gap though nature of the sediments undergoes a change, quality does not pose a problem. Arenaceous contents in the alluvium show a conspicuous increase. The thickness of sediments usually do not exceed 100 metres. As in its western extension, in this part also aquifers wherever present are of limited extent. Groundwater development problem in this belt is two fold, firstly the non-availability of extensive aquifer horizons and secondly the presence of negative hydrological boundaries restricting the yield potential of the aquifers, except locally; e. g., in the Bhagalpur embayment.

(ii) *Coastal Alluvia*

These include the east and west coast alluviaum, plains of Gujarat and the delta of Ganga and Brahmaputra.

East Coast : A belt of alluvial deposits extends more or less continuously along the east coast from Ganga delta to Cape Comorin. The width of this belt is variable but it does not exceed 80 kilometres. At places hard rock exposures considerably reduce the width e. g., south of Chilka lake in Orissa and near Pondichery. Near the mouth of the great rivers Mahanadi, Godavari, Krishna and Kaveri, broad alluvial plains extend inland for many miles.

The thickness of the alluvium is variable and average about 150 metres.

The sediments comprise sands of various grades, silt and clay. These sand horizons form promising aquifers often occurring under confined conditions.

In the Basta-Haldipada area of Balasore district, Orissa the studies indicate an increase in the depth to fresh water zone and the thickness of saline water bearing sediments towards the sea. Within the saline tract fresh water bearing formation occur below the saline water bearing horizons separated by a clay bed.

(b) *Western Coast :* Unlike the eastern coast, there is no continuous stretch of alluvium along the western coast. The alluvial deposits are chiefly restricted to the vicinity of the small streams draining the western ghats or of the back waters which have been out-off by sand bars along the coast.

Alluvial plains connect hills of Bombay island with those of Salsette. Further north these plains gradually increase in extent and merge in the Gujarat alluvial flat. The thickness of the alluvium is over 100 metres near Sanand. At Rajpipla, the alluvium contains several pebble and sand beds.

(c) *Gujarat Alluvial Flat :* The great plain of Gujarat commences near Daman and continues as far as the Rann of Kutch. It has a width of about 48 kilometres near Surat and 96 kilometres near Baroda. The alluvium consists of Upper brown clays and *Kankar* and the lower sands and sandy clays with occasional gravel.

In Mehsana district, alluvial deposits are thick and extensive which forms a part of the sediments of Cambay basin. The maximum thickness of alluvium is indicated to be about 700 metres. Three major aquifer horizons occur between the depth range of 110-330 metres. Western half of the area is part of an extensive artesian basin extending from Banaskantha district in the north to Kaira district in the south. Of the three aquifers mentioned the uppermost aquifer (within a depth of 176 metres) has reached its optimum development. Further development has to be restricted to the remaining two aquifers.

The alluvial deposits are very thin and meagre in Kutch. The alluvial belt in Kutch varies from 5 to 16 m. in with rather an insignificant thickness.

(*iii*) *Ganga Delta*

Bengal basin was the site of continuous sedimentation throughout most of the Tertiary period. With formation of the Garo-Rajmahal gap during the lower Pliestocene, period, the Bengal basin was integrated with the foredeep area of the main Gangetic basin. Previous to this Bengal basin was receiving sedimentation from the peninsular shield lying to the west and also from the eastern terrain. The formation of the Garo-Rajmahal gap entirely changed the picture of sedimentation, as the Bengal basin was then exposed to the drainage from the Himalayan side which accelerated the pace of sedimentation. During Himalayan orogeny, with each phase of upheaval, the pace of sedimentation stepped up building up of the vast alluvial flats as we witness today. Flood plain environments prevalied in the upper reaches which gradually merged southwards with the Mangrove swamps, estuarine and marine environments.

Results of the drilling operations indicate that the sedimentary succession consisting of a basal clay bed which is overlain by sequence by a basal gravel, sand, varying in fraction from coarse to fine, silt and clay. The gravel bed is more or less persistent whereas the sand horizons, though extensive but are inter connected.

In northern parts of the delta, productive aquifers are available for development, within the depth range of 75 to 120 metres ; in the central part such aquifers occur in the depth range of 90 to 200 metres and in the southern parts near the coast the fresh water aquifers exist only below 250 metres. However, those aquifers that exist above the depth of 250 metres, near the sea coast, generally have mineralised formation water.

In the coastal tracts of Midnapur area, fresh water aquifer horizons occur below a depth of 155 metres. This is overlain by interconnected group of aquifers containing saline water. The saline water and fresh water aquifer systems are separated by a clay bed which is about 6 metres thick. This clay bed appears to persist from Midnapur coastal area upto Baripada in Orissa. The group of saline water aquifers occurs within the depth range of 15 to 150 metres. There are also pockets of freshwater bearing zones within these saline aquifers. This saline-water aquifer is overlain either by surface clay which increases in thickness from west to east or southeast or by the dune sands. The dune sands attain a maximum thickness of 15 metres and contain fresh water lenses. These dune areas act as sources of local recharge to the near surface ground-water body.

(*iv*) *Intermontane Valleys*

The Himalayan intermontane valleys are all in their early stages of development. They have undergone rejuvination over and over again with every upheaval of their inner ranges which account for their varying lithological characters and structures.

In contrast, the Peninsular valleys are generally in a mature stage of their development. These are broad and shallow, their gradient low and have attained almost the base level of erosion except the Narmada valley.

(a) *Kashmir Valley :* Kashmir valley trending in a NW-SE direction lies between the Pir Panjal and Zanskar ranges. Within these intermontane structure whose bed rock comprises rocks ranging in age from Cambro-Silurian to Jurassic, thick deposits of Quaternary sediments have been laid down, totalling a thickness of neraly 2100 metres. The Quaternary sediments include the Karewas (fine grained sands, loams and blue clays) river terraces, river alluvia, pebble beds and recent moraines. The valley is fringed on the flanks by outwash deposits in the form of alluvial fans. The valley fills show definite coarsening of sediments towards the periphery.

Hydrogeological studies indicate that groundwater occurs under confined and unconfined conditions in the unconsolidated sediments. Water table intersects the land surface almost continuously along the scarps formed of Karewas, river terraces, alluvial fans, and glacial moraines and issues in the form of springs. In the lower reaches of the alluvial fans below the line of springs artesian waters occur in the outpinching sand-pebble beds outflowing at the land surface when tapped by tubewells. Such conditions also prevail at the base of trap hills in the talus fans.

Groundwater development programme in the valley will involve proper utilisation of the springs, exploiting the artesian belt, and productive horizons in the Karewas.

(b) *Donn, Bahl, Nurpur valleys :* These longitudinal valleys, situated in the outer Himalayas of Uttar Pradesh and Himachal Pradesh, constitute broad expanse of boulder-gravel and talus fans. Boulder-gravel and sands are the chief waterbearing formations which vary both in thickness and coarseness. In central parts of the valley, the aquifers generally have a confined to semiconfined disposition. Tremendous recharge facilities coupled with hydrogeological set-up provide favourable conditions for large groundwater storage. Quality of water will pose no problem in groundwater development programme but special rigs may be required to drill through hard boulder-gravel formations.

(v) *Valley-fill Areas :*

The valley fills assume considerable importance as sources of water supply lying as they do in otherwise hard rock terrain, arid regions of mineralised groundwater. Although the thickness of valley fill materials does not generally exceed 60 metres they contain saturated sand-gravel-pebble beds having high permeability and satisfactory recharge potential,

Valley fills have been located in the catchments of Banas, Singhana, Kantli, Luni and Khari rivers. Quantitative assessments made of these valley fills have indicated their large groundwater development potential.

(vi) *Intra-Cratonic Basins*

These include Narmada, Tapi and Purna basins of central India.

Alluvial materials comprising of sand and gravel have attained a thickness of about 90 metres in Narmada valley. The studies carried out in recent past have indicated possibility of large scale development of groundwater in this valley.

In the Purna valley though the alluvial fill attains a maximum thickness of 325 metres, the groundwater development possibilities do not exist in view of inadequate thickness of aquifer materials.

In Tapi basin, however, only a small area around Rajora and Raver, where the thickness of saturated material is of the order 40-50 metres, hold promise for groundwater development on a moderate scale.

(*vii*) *Aeolian Sand Tracts*

Large areas in western Rajasthan as also the coastal tracts are covered by aeolian sands. In coastal areas these attain a thickness of as much as 20 metres. In Rajasthan, however, these attain rather an extraordinary thickness. The sand mantle concealing the subsurface formations often record a thickness of the order of 100 metres. Dune sands are known to rise about 60 metres above the surrounding plains.

These sands often contain a zone of saturation which is relatively thin. This constitute important sources for domestic water supply not only in the arid region where fresh water is scarce but also in the coastal tracts. Such fresh water lenses in the sands have been recorded in the eastern coastal areas as well as various parts of Rajasthan. In view of the limited extensions of the fresh water lenses they are of no significance for any groundwater development programme but would continue to be the mainstay for domestic fresh water supplies.

B. Areas Underlain By Semi-consolidated Sediments

These include the Tertiaries and Mesozoics of Assam, Cambay basin, Eastern coastal areas, and western Rajasthan. The terrestrial freshwater deposits comprising the Gondwanas are also included in this group.

(*i*) *Palaeo-Mesozoic-Tertiaries of Western Rajasthan :* The Mesozoic and Tertiary formations of western Rajasthan have been dealt with separately, in as much as they lie in the arid tracts and the problems of groundwater occurrence and development are quite different from those of other areas. Western Rajasthan is isolated from the prolific aquifer of the Sindhu-Ganga basin by the sub-terrannean extensions of the Aravallis or reverse hydraulic gradient. No significant subsurface recharge of aquifers in western Rajasthan appears possible from the Sindhu-Ganga basin. It has, therefore, to depend for its replenishment on local rainfall which does not exceed 250 mm. per annum.

The most productive aquifer in western Rajasthan is top 300 metres of the Lathi group of sandstones. Other promising aquifers include the Barmer sandstones, and the Parihars. Tertiaries in Rajasthan invariably yield highly mineralised water.

In view of the limited recharge potential of the aquifers in western Rajasthan it is imperative that tracer studies including ground water dating be carried out to establish the movement and the age of groundwater. This would help in formulating the developmental plans to safeguard that no mining of groundwater takes place.

(*ii*) *Coastal Areas*

Tertiaries and the Mesozoic of coastal areas include the Baripada beds, Cuddalore sandstones, Rajamundry sandstone the Tiruvakkarai beds, Varkalli formations, the Himmatnagar sandstones, the Bhuj beds *etc.* These comprise a thick sequence of sea-ward dipping sediments including clays, sandstones and conglomerates with occasional beds of lignite. These formations not only outcrop at surface but also at places underlie the coastal alluvia. Those lying on the eastern coast constitute one of the most prolific aquifers occuring under artesian conditions occasionally outflowing at land surface when tapped through tubewells. Those in the Gujarat and Saurashtra coastal areas, often pose salinity problems.

(*iii*) *Gondwana Basins*

The rocks of the Gondwana system outcrop in a number of more less isolated basins following approximately the courses of some of the existing rivers of the Peninsular shield. They also occur as outliers on northern side of the Sindhu-Ganga-Brahmaputra alluvium principally in Assam and Kashmir. These are chiefly made up of alternations of sandstones and shales with coal seams. The intrusions of basic volcanic rocks are not infrequent. The sandstones are generally argillaceous which restricts free movement of groundwater. Presence of numerous planes of structural weaknesses in these formations normally favour groundwater occurrence and movement. Poor permeability of the Gondwanas preclude large scale groundwater development. In such terrains groundwater development is possible only in such areas where geomorphological conditions are favourable.

The coal seams present in these formations are often pyriteous. This often contributes to the acidic nature of groundwater; also reducing conditions prevail. As a result, groundwater of this formation locally belongs to the regime of 'mine water'.

In the Gondwanas of Hazaribagh, artesian conditions are known to exist.

C. *Areas Underlain By Hard Rocks*

The regime of groundwater in hard rocks is strikingly different from that of unconsolidated and semi-consolidated sediments. Hard rocks possess secondary porosity which are generally of two types : firstly joints, fissures and fractures as a result of tectonic features while the second is more in the nature of intergranular porosity due to the action of weathering agents. The groundwater reservoir in hard rocks is genrally shallow.

Its shape, depth and lateral extent are variable depending upon the lithology and structure of the parent rock. On the basis of lithology and structure hard rocks are divisible into four main categories each of which

have distinct hhydrogeological faetures. These are (i) Crystalline rocks including granites, gneisses, schists, amphibolites and associated types with their intrusives *(ii) the Deccan Traps (iii) the compact sedimentary formations,* namely Cuddappah, Delhis and Vindhyans and to some extent even Gondwanas and (iv) the carbonate rocks which are characterised by development of solution channels.

Storage of groundwater in hard rock reservoirs is controlled by zone of weathering and the interconnected plains of structural weaknesses in the parent rock. In the rocks falling in the category (i) and (ii) described earlier, the weathered mantle has a greater capacity to store and yield water than the fractured zones. The rocks falling under category (iii) are more susceptible to fracturing than weathering; and rock's control of fracture porosity on groundwater storage is apparently more.

Groundwater reservoirs in the hard rocks being shallow, the movement of groundwater is controlled largely by topography. The flow pattern gets locally modified due to the presence of various geotectonic features. Dykes and quartz veins act as barriers to groundwater flow while faults and shear zones may act either as conduits or barriers depending on whether they are open or closed.

Within the weathered zone groundwater movement is relatively shallow and is almost restricted to a zone extending from the drainage divide to valley base. Groundwater occurs in this zone generally under unconfined conditions.

Flow of groundwater in the Karstic limestones has its own peculiarities. Here it is the nature of the solution channels that control the groundwater movement more than the land topography. Often watershed leakages in such terrains takes place.

Geochemistry of groundwater is controlled by the bulk chemistry of the host rock, the overlying soils, and the locale of the sample in the groundwater flow system. As such it shows vide variations.

Hard rocks have limited groundwater yield potential. However, the present stage of knowledge and development is indicative of large groundwater development possibilities in such terrains. Existing potential could be greatly increased by adopting measures for groundwater reccharge, improving groundwater exploitation methods, and groundwater management.

General Problems of Groundwater Development

The Account of the hydrogeological set-up of the various parts of the country presented in the preceding paragraphs give an idea of the varied and complex nature of the groundwater development problems

in India. Some of these problems of a limited magnitude are exclussive and particular to certain areas or basins and are purely governed by local conditions. It is to be pointed out that a large number of so-called water supply problems are in fact nothing but well-efficiency problems. At the same time there exist other problems of a more fundamental nature. While describing the hydrogeological set-up of respective areas an effort has been made to enunciate the nature of their special problems. In the following paragraphs an attempt will be made to present the more general problems which are common to groundwater development throughout the country.

Groundwater basin is the fundamental unit to be considered for judicious groundwater development and management. Its shape and extent, to a very large measure, results due to the influence of geomorphology and geology. Although the existence of several groundwater basins are known, their exact boundary and sub-boundaries are yet to be defined. This problem undoubtedly is of immediate importance for planning our ture programmes.

Again, within the basin itself a variety of hydrogeological phenomena are easily observed, such as areas of deep water levels, areas of flowing conditions, areas of quality hazards and so on. A meaningful interpretation of these features is of vital importance in devising judicious developmental measures. This interpretation is largely dependent upon a proper understanding of the hydrological cycle as a whole and in obtaining full knowledge of the source of water, the nature of recharge, physics and chemistry of the flow systems and mode of natural discharge. In the case of deep and extensive sedimentary basins, the conventional water table map itself provides only a fragmentary part of the answer. It needs no emphasis that an understanding of the geological framework of the hydrological system is only the beginning of the problem. It is, therefore, necessary to determine the significant hydrostratigraphic units, their description and mapping while taking up any basinwise study. It is also being increasingly realised that lack of country wide programme of data collection is indeed hampering groundwater studies and will be a hindrance for future studies as well.

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